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USER GUIDELINES, MEASUREMENT STRATEGIES, AND OPERATIONAL FACTORS FOR DEPLOYMENT OF *IN SITU* GAMMA SPECTROMETRY AT THE FERNALD SITE

FERNALD CLOSURE PROJECT
FERNALD, OHIO

DECEMBER 2004

U.S. DEPARTMENT OF ENERGY

20701-RP-0006
Revision 1, Final

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TABLE OF CONTENTS

5796

TABLE OF CONTENTS
(Continued)

Page

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

A1PII	Area 1, Phase II
A2PI	Area 2, Phase I
ALARA	as low as reasonably achievable
ASL	analytical support level
ccpm	corrected counts per minute
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CLP	contract laboratory program
cm	centimeter
cps	counts per second
DGPS	differential global positioning system
DOE	U.S. Department of Energy
dpm	disintegrations per minute
DQO	data quality objective
EGAS	Environmental Gamma-ray Analysis Software
EMS	Excavation Monitoring System
EPA	U.S. Environmental Protection Agency
ET	excavator tool
FCP	Fernald Closure Project (current site name)
FEMP	Fernald Environmental Management Project (former site name)
FOV	field of view
FQCS	Field Quality Control Station
FRL	final remediation level
FWHM	full width at half maximum (peak height)
g/cm^2	grams per square centimeter
GM	Geiger-Mueller
GPS	global positioning system
HPGe	high purity germanium (detector)
IRDP	Integrated Remedial Design Package
keV	kiloelectron volts
LAN	Local Area Network
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MCA	multi-channel (pulse height) analyzer
MDA	minimum detectable activity
MDC	minimum detectable concentration
µg/g	micrograms per gram, equivalent to parts per million (ppm)
mph	miles per hour
NaI	sodium iodide
OEPA	Ohio Environmental Protection Agency
OSDF	On-Site Disposal Facility

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued)

PCI	peripheral component interconnect
pCi/g	picoCuries per gram
ppm	parts per million
PSP	Project Specific Plan
QA/QC	Quality Assurance/Quality Control
RMS	Radiation Monitoring System
RSS	Radiation Scanning System
RTIMP	Real Time Instrumentation Measurement Program
RTRAK	Radiation Tracking System
DSDP	Demolition Soils and Disposal Project (DS&DP)
SCQ	Sitewide CERCLA Quality Assurance Project Plan
SED	Sitewide Environmental Database
SEP	Sitewide Excavation Plan
SP5	Soil Stockpile 5
SW846	Solid Waste, Tracking No. 846
USID	uranium in soil integrated demonstration
WAC	waste acceptance criteria
WAO	Waste Acceptance Organization
WAP	Waste Acceptance Plan

1.0 INTRODUCTION

This document summarizes the measurement systems and protocols used by the Real-Time Instrumentation Measurement Program (RTIMP) at the Fernald Closure Project (FCP) and addresses two basic questions:

1. "How will *in situ* gamma spectrometry be used at the FCP?"
2. "How will FCP personnel address variables that have a potential impact on *in situ* gamma spectrometry data?"

The measurement systems are discussed in Section 2.0 and the protocols are outlined in Sections 3.0 and 4.0. Section 5.0 provides additional information on technical topics related to detector calibrations, minimum detectable concentrations, radium corrections, moisture corrections, data verification and validation, and measurement uncertainties. Answers to the questions posed above are summarized for the user throughout the document in the guidance subsections at the end of each section.

1.1 BACKGROUND

Questions and comments from the US Environmental Protection Agency (EPA), the Ohio EPA (OEPA), the US Department of Energy (DOE), and Demolition Soils and Disposal Project (DSDP) personnel indicated the need to bridge the gap between the primarily analytical information contained in reports documenting method validation studies and other efforts at the FCP and programmatic remediation design documents such as the Waste Acceptance Plan (WAP, DOE 1998b), the Sitewide Excavation Plan (SEP, DOE 1998a), and Integrated Remedial Design Packages (IRDPs). This document bridges that gap by providing user guidelines, data interpretation guidelines, measurement strategies and approaches, information related to operational and technical factors that could affect data collection, and strengths and limitations of various *in situ* gamma spectrometry systems. While this document will be beneficial to anyone involved with the RTIMP, it is primarily aimed toward FCP project personnel who:

- Plan *in situ* gamma spectrometry data collection;
- Collect *in situ* gamma spectrometry data;
- Interpret *in situ* gamma spectrometry data;
- Integrate *in situ* gamma spectrometry data with other data or into engineering designs; and
- Make decisions based upon *in situ* gamma spectrometry data.

Figure 1-1 indicates the relationship between this document (hereafter referred to as the "User's Manual") and other driver documents related to analytical, quality assurance, and remediation operations issues. The User's Manual contains information from method validation studies that has been integrated with the technical guidelines contained in the SEP (which provides a summary of the overall approach to remediation at the FCP). The guidance provided in the User's Manual is expressed in the form of *in situ* gamma spectrometry measurement strategies and approaches for meeting soil program objectives that can be incorporated into area-specific reports such as PSPs, IRDPs and certification reports. Table 1-1 summarizes the types of information contained in the User's Manual. As implied in Figure 1-1 and Table 1-1, the User's Manual is the key document relative to incorporating *in situ* gamma spectrometry into routine soil remediation operations.

Revision B of this manual was issued in July 1998. Prior to issuance of that version of the manual, various studies had been carried out at the FCP to validate the use of *in situ* gamma spectrometry for measurement of radionuclides in soils at the site. In particular, in 1997 a report on a series of method validation studies was issued. Those studies addressed analytical aspects of *in situ* gamma spectrometry such as precision, accuracy, detection limits, robustness, comparability with laboratory analytical data, and data quality levels. Results from those studies were incorporated into Revision B of this manual. Since that time, additional studies have expanded the work done prior to issuance of Revision B. The most recent versions of the reports documenting these studies are discussed in Section 1.1.1. This report has been updated using results from those studies.

Since the issuance of Revision B of this manual, several additional NaI detectors have been purchased and mounted on a variety of scanning platforms. These new platforms are discussed in detail in Section 2.0, along with those previously in service.

There have been several significant improvements in the software used to analyze NaI spectra since Revision 0 of this document was issued in January 2004. These changes precipitated a reexamination of the uncertainties and minimum detectable concentrations associated with NaI measurements. Additionally, a hand-held system called the nanoSPEC has been added to arsenal of NaI detectors that are available for use in screening soils at the Fernald Closure Project for radioactive contaminants. These new features of the real time scanning program will be described at appropriate places throughout this manual.

1.1.1 Primary RTIMP Technical Documents

The following section describes the primary technical documentation for the *in situ* gamma spectrometry systems used by the RTIMP team to perform its primary measurement functions. A number of these documents are referred to above and are described here in greater detail. The documents encompass performance testing and documentation that has been going on since approximately 1996, following the issuance of the OU5 Record of Decision (ROD). Real-time gamma spectrometry technologies were selected to play a major role in supporting the extensive needs for radiological characterization and measurements associated with the remedial actions outlined in the ROD. These documents cover the overall development and validation of real-time methods for use in soil remediation.

Since 1997 much of the development and documentation of these technologies has been carried out under DOE EM50's Accelerated Site Technology Deployment (ASTD) program under two sequential three-year projects. The first project was known as the "Integrated Technology Suite (ITS)" and the second as the "Integrated Excavation Control System (IECS)." Project partners included Fluor Fernald, Argonne National Laboratory (ANL), Idaho National Engineering and Environmental Laboratory (INEEL), DOE-Fernald, and DOE's (former) Environmental Measurements Laboratory (EML), now affiliated with the U.S Homeland Security Department.

The ITS project encompassed deployment of the mobile sodium iodide (NaI) systems RTRAK and RSS as well as the tripod mounted high purity germanium (HPGe) systems. IECS added the Excavation Monitoring System (EMS), which deploys gamma detectors on the arm of an excavator, and a GPS-based excavation volume measurement system employing the John Deere Gator™ all terrain vehicle.

The primary technical documents are listed in Table 1-2, along with the current version status and date. No further key documents will be developed to support the FCP real-time program. Some of the documents have been superceded to a large extent by others in the table, but may still contain important system documentation. The following paragraphs describe the purpose and content of the documents listed as well as any planned or expected revisions of them.

The first document listed in Table 1-2 is better known as the "User's Manual" for the real time systems (this document). It is an overarching document intended to assist project managers and system users alike in the actual use of the systems to support soil remediation. It provides (1) descriptions of the systems and their performance characteristics; (2) methods, procedures and protocols for their use in soil remediation, and (3) discussions of a wide variety of technical and implementation issues. This document provides a complete picture of the application of these systems at the FCP. Greater technical detail can be found in other supporting documents.

Revision 0 of this document included an extensive reorganization of Sections 2, 3, 4 and 5 of the prior version, the addition of the Gator and EMS platforms, PSP overviews for various remediation phases, and a number of other additions reflecting technical advances in the program. The construction and use of the calibration pad for calibrating the NaI-based systems is perhaps the most significant improvement made in prior years. Previously, the systems had been calibrated for isotopic analysis using contaminated field locations where varying U-238, Th-232 and Ra-226 levels had been characterized by *in situ* HPGe measurements. The current version (Revision 1) reflects improvements made since Revision 0 was issued, including significant enhancements made in 2004. The recent programmatic enhancements described in this revision include improvements to the software that analyzes NaI gamma ray spectra and the addition of a hand-held NaI detector that can be used in high contamination areas to avoid contaminating vehicles that carry other NaI detectors.

The second document in Table 1-2 is known as the "Comparability Study." This report represents the culmination of several years of effort that compared the performance of *in situ* HPGe to laboratory methods for soil characterization. The purpose of the studies was to evaluate the suitability of HPGe for performing a number of key measurement functions in the soil program, up to and including final certification of achieving final remediation levels (FRLs) in soil remediation areas. To this end, substantial technical detail is provided in the report supporting the general application of *in situ* HPGe to soil remediation. On the basis of this study, the FCP proposed to regulators the use of HPGe for a major role in the program. Regulators ultimately approved its use for all proposed applications except final certification. They cited concerns with data quality for radium-226 (Ra-226) measurements, which are affected by radon disequilibrium in soils as well as by effects of atmospheric radon, both of which contribute some uncertainty to the measurements.

The "RTRAK Applicability Study" was finalized on the same date as the Comparability Study (January 1999). The RTRAK study examined performance characteristics and data quality for this and the similar RSS mobile NaI systems by making a series of measurements over contaminated areas that were characterized by HPGe. The studies resulted in a revised field calibration for the RTRAK as well as estimates of measurement uncertainty and minimum detectable concentrations (MDCs) for total uranium, Ra-226 and thorium-232 (Th-232). The field calibration was done by regression analysis of detector response to estimated soil concentrations in the various contamination areas surveyed. This method of calibration has been replaced by measurements performed on the calibration pad, while calculations of uncertainties and MDCs based on measurements on the calibration pad have since replaced those in the RTRAK Applicability Study.

The 2001 "Calibration Report" (DOE 2001) documents the initial formal calibration of NaI systems on the calibration pad. Results of the calibrations included the determination of coefficients for efficiencies for uranium-238 (U-238), Ra-226 and Th-232, as well as for mutual interference factors for these isotopes. The results of the initial calibration were verified via a point source calibration of the same detectors using certified sources as well as through a check of field results obtained using the previous field calibrations. Appendices of the report discuss the methodology for performing calibrations on the pad, the distribution of discrete sources used on the pad, the preparation of these sources using available materials at the FCP, the point source calibration method, and the field data comparison.

The February 2002 "Excavation Monitoring System (EMS) Report" (DOE 2002a) documents the development and deployment of the EMS at the FCP by ASTD partners, principally INEEL. The EMS was based on a previous technology developed by INEEL known as the Warthog. Under the IECS project, the system was re-engineered and new system software was developed. Final testing of the EMS was performed in December 2001 using the calibration pad as a test bed and calibration standard. A good deal of the report is devoted to EMS applications in deep excavations and in trench excavations. A protocol for applying geometric corrections for measurements in non-flat terrain is presented in the report.

The "Minimum Detectable Concentration/Waste Acceptance Criteria (MDC/WAC) Trigger Level Report" (DOE 2002c) was issued as draft final in August 2002. An addendum adding results for the Gator was added in October 2002. This report presents methodology and formal calculations of MDCs and WAC trigger levels for all NaI systems currently in use. It supercedes previous efforts in this area, including the estimates presented in the RTRAK Applicability Study. This report was, in turn, superceded by ANL 2004.

The September 2002 draft of the "NaI Uncertainty Report" (DOE 2002d) is a companion to the MDC report. ANL is the primary author of both reports. The NaI uncertainty report estimates uncertainties in NaI soil measurements from significant contributing sources, including counting error. Like its companion report described above, this report was also superceded by ANL 2004.

The December 2002 "Software Operations Manual" (INEEL 2002) for the EMS and other NaI systems was written by INEEL. This report provides screen-by-screen instructions for system operators and describes information stored in output files, as well as details of the spectrum analysis process using the embedded Environmental Gamma-ray Analysis software (EGAS). Information in this report represents the culmination of several years of system software development carried out by INEEL. An additional updated revision of this report, Revision 3.1, will be issued to reflect significant software changes made in 2004.

1.2 MANDATORY VS. RECOMMENDED

Some of the guidelines and text in this manual are recommendations. That is, the guidelines are to be followed as the professional judgment and the experience of the user dictates. However, to maintain data integrity, some of the guidelines and text are to be followed exactly. In this regard, the language below specifies whether a particular guidance or section of text is mandatory, recommended, or explanatory.

Shall, Will, Must: These words refer to practices and/or operations that are mandatory. The user is to follow the guidance or text exactly.

Would, Should: These words are used to identify recommendations to the user. Flexibility is implicit in these words and professional experience and judgment may dictate that an alternative approach is more appropriate.

Could, Can Be, May: These words indicate that multiple possibilities exist for a particular practice, operation, or usage. They imply neither mandatory nor recommended guidance.

1.3 OBJECTIVES

Information relevant to carrying out *in situ* gamma spectrometry measurements at the FCP is contained not only in the method validation studies listed earlier, but is also derived from the scientific literature, experience at other DOE institutions, and from the cumulative experience gained at the FCP. Much of this information is discussed in the references listed in the Reference section. Information from these diverse sources has been used to achieve the following User's Manual objectives:

- Translate pertinent analytical information contained in the various method validation studies into "easy to understand" user guidelines
- Integrate diverse technical information contained in the scientific literature with method validation information and with *in situ* gamma spectrometry data already acquired in support of soils remediation operations to establish "easy to understand" user guidelines
- Document "lessons learned" type information based upon the cumulative experience of Fluor Fernald and DOE personnel
- Delineate strengths and limitations of the *in situ* gamma spectrometry techniques for use in soil remediation.

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- Document "lessons learned" type information based upon the cumulative experience of Fluor Fernald and DOE personnel
- Delineate strengths and limitations of the *in situ* gamma spectrometry techniques for use in soil remediation.

1.4 REPORT FORMAT

The general format and organization of the User's Manual are loosely patterned after "help" manuals for common desktop software. The manual has several sections of related topics; each topic has a stand-alone discussion. As applicable, each topic also has a guidance section, which provides rules, suggestions, and "how-to" comments. At the end of the discussion, the reader is directed to other related topics.

This document is divided into four general categories of topics: Section 2.0 presents a summary of the *in situ* gamma spectroscopy systems used at the FCP; Section 3.0 discusses the use of these systems during predesign investigations, soil excavation, precertification, and certification activities; Section 4.0 provides characterization, data interpretation, and operational guidelines; and Section 5.0 discusses relevant technical topics. Each topic within a section is, to a large extent, a self-contained subsection with bulleted guidance following a general discussion of the topic and a "see also" list of related document sections.

In addition, this User's Manual has References, a Glossary and a list of Acronyms. The References section contains a list of relevant scientific literature, including both FCP publications and outside publications. The List of Acronyms and Abbreviations appears before the Introduction (Section 1.0) to this manual and a Glossary appears at the end of the manual. In addition to definitions of terms, the Glossary directs readers to sections of the manual related to a given definition.

TABLE 1-1
TYPES OF INFORMATION CONTAINED IN USER'S MANUAL

Type of Information	Information Used in Following Documents
Technical Guidelines	WAP, SEP, IRDP
Measurement Strategies	IRDPs, Certification Report
Measurement Approaches	IRDPs, PSPs, Certification Report
Technical Direction	PSPs
Data Interpretation Guidelines	Predesign Investigation Reports, IRDPs, Certification Reports
Factors Potentially Impacting Data	IRDPs, PSPs
Strengths and Limitations	IRDPs, PSPs

TABLE 1-2
LIST OF PRIMARY DOCUMENTS FOR THE REAL-TIME GAMMA SYSTEMS USED AT FERNALD

Report Title	Date (reference)	Status
User Guidelines, Measurement Strategies, and Operational Factors for Deployment of *In situ* Gamma Spectrometry at the Fernald Site	December 2004 (this document)	Rev B released July 1998. Rev 0 released January 2004; Rev 1 issued December 2004.
Comparability of *In situ* Gamma Spectrometry and Laboratory Data	January 1999 (DOE 1999a)	Rev 1, Final
RTRAK Applicability Study	January 1999 (DOE 1999b)	Rev 2, Final. Much of this document has been superceded by more recent reports, particularly with regard to calibration and MDCs.
Calibration of NaI *In situ* Gamma Spectrometry Systems	March 2001 (DOE 2001)	Rev 0, Final
Development and Deployment of the Excavation Monitoring System (EMS)	April 9, 2002 (DOE 2002a)	Rev 0, Final
Minimum Detectable Concentrations and WAC Trigger Levels for *In situ* NaI Gamma Spectrometry Systems Used at the Fernald Environmental Management Project	August 2002 (DOE 2002c)	Final Draft. This final draft was approved by OEPA on September 19, 2002. A draft addendum for the Gator is dated October 2002. Much of the material in this report has been superceded by Report ANL/EAD/TM/04-02, Reference ANL 2004
Measurement Uncertainties for the *In situ* NaI Spectroscopy Systems Used at the Fernald Environmental Management Project	September 2002 (DOE 2002d)	Working Draft. Much of the material in this report has been superceded by Report ANL/EAD/TM/04-02, Reference ANL 2004
FEMP Sodium Iodide and Excavation Monitoring System Software Operations Manual	December 2002 (INEEL 2002)	Version 2.0 issued December 2002. Version 3.1, reflecting significant software improvements is expected to be issued early in 2005.
Measurement Uncertainties and Minimum Detectable Concentrations for the In Situ NaI Gamma Spectrometry Systems Used at t he Fernald Site, ANL/EAD/TM/04-02	June 2004 (ANL 2004)	Final. Information in this report supercedes much of the information in DOE 2002c and DOE 2002d.

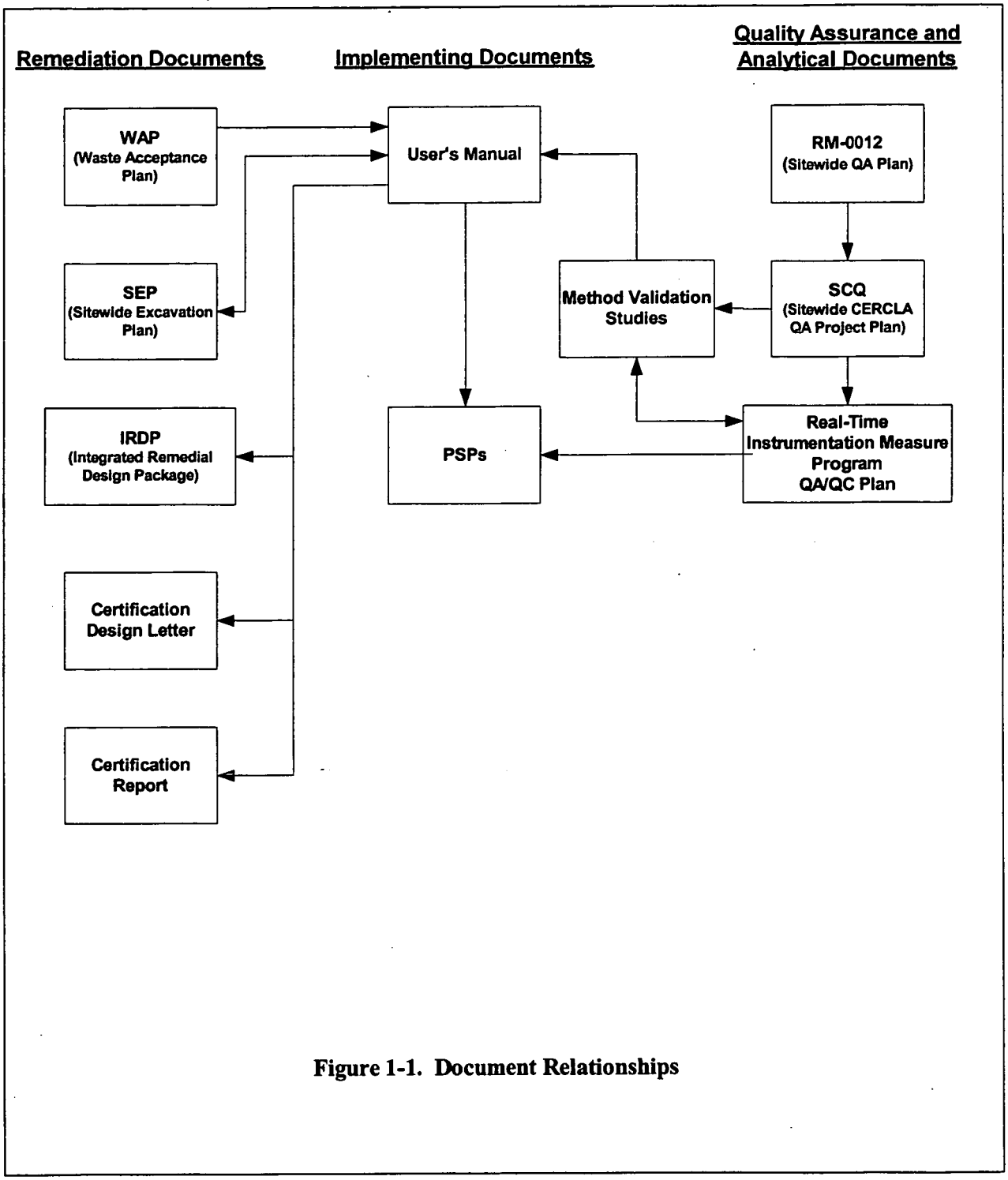


Figure 1-1. Document Relationships

2.0 *IN SITU* GAMMA SYSTEMS OPERATED AT THE FCP

The purpose of this section is to describe the *in situ* gamma spectrometry systems used at the FCP, the general deployment of these systems in support of soil remediation, and the strengths and limitations of the systems when performing *in situ* measurements. The latter discussions are intended to provide a background for understanding the performance of the systems. A key role for the RTIMP group is application of various HPGe and NaI systems to the wide variety of DSDP measurement requirements. Detailed discussions of actual methodology and deployment of the systems in the various phases of the soil remediation process are presented in Section 3.0.

Two main types of *in situ* gamma systems are used at the FCP, HPGe- and NaI-detector systems. Certain situations or conditions may be more favorable for the use of one type of detector rather than the other. Similarly, certain remediation operations require measurements that can be provided only by one or the other of the two detector types. In order to decide which piece of equipment is most appropriate, remediation project personnel need to clearly define the measurement objectives. The process of developing data quality objectives (DQOs) in advance of the actual field work will help to define what data needs to be collected, and the associated data quality levels. Tables 2-1 and 2-2 provide a basic overview of the uses of HPGe and NaI detectors, and also specify the data quality levels, which are likely to be required for these uses. These data quality levels are consistent with descriptive information in the Sitewide CERCLA Quality Assurance Project Plan (SCQ).

The HPGe systems are tripod or EMS mounted (Section 2.5), commercially available detector systems for making high resolution measurements of gamma emitting radionuclides. These systems acquire data in a stationary mode and provide more accurate measurements than the NaI systems. For both systems, the U-238 result (pCi/g) is generally reported as total uranium (µg/g or mg/kg). This total uranium concentration result is obtained by multiplying the U-238 activity in pCi/g by 2.99. The field of view for HPGe systems can be adjusted by changing the height of the detector relative to the ground surface. The HPGe detectors can be configured to accept a collimator if necessary to reduce the effect of radioactive material outside the normal detector field of view.

The NaI-based systems employ a variety of vehicles as mobile deployment platforms. Fully assembled systems are not commercially available. Operational NaI-detector platforms include the RTRAK (a full sized farm tractor; Section 2.2), Radiation Scanning System, the RSS (a manually-pushed three-wheeled cart; Section 2.3), the Gator™ (a modified John Deere all-terrain vehicle; Section 2.4) and the EMS (an

excavator mounted system; Section 2.5). A hand-held NaI detector, called the nanoSPEC, has recently been placed into service for use in walkover surveys of areas with elevated contamination levels to avoid decontaminating the wheels or chassis of the vehicles that carry other NaI detectors (Section 2.6). All of the NaI platforms, except the nanoSPEC, use uncollimated 4-inch by 4-inch by 16-inch NaI crystals. Detector crystals are mounted at a height of 31 cm (1 foot) above the ground, except for the EMS, which deploys detectors (either HPGe or NaI) at variable heights. The nanoSPEC uses a 4-inch diameter by 4-inch high cylindrically shaped NaI crystal. Each detector system is calibrated separately. Since much of the discussion in this guidance applies to all the mobile platforms that deploy NaI detectors, they will be referred to collectively as NaI systems. The NaI systems have also been referred to as Radiation Monitoring Systems (RMS) in other FCP documents.

NaI systems are typically used in a mobile mode to survey large areas and map the distribution patterns of U-238, Th-232 and Ra-226 activity. The mapped patterns and individual measurements are used to identify elevated areas of radioactivity or hot spots (hot spots are discussed in detail in various places in Section 3.0). The standard operational mode for the NaI platforms is a vehicle speed of 1 mile per hour (mph) and spectrum acquisition time of 4 seconds. All systems are equipped with a global positioning system (GPS) receiver, which is used to assign precise geographic coordinates to each 4-second spectrum. The GPS information is automatically coupled to each 4-second gamma ray spectrum, except in the case of the nanoSPEC, where GPS linkage to the spectra must be accomplished manually at this time. All measurements are plotted on a base map to show patterns of contamination.

The HPGe and NaI systems are complimentary in that each has different strengths that are helpful for a thorough characterization of a soil remediation area. NaI systems have the ability to rapidly survey large areas, while HPGe systems provide more definitive characterization of smaller areas, including areas of interest identified by NaI measurements. A complete overview of the use of these systems at the FCP is provided in Section 3.0.

The remainder of this section provides more detailed descriptions of each NaI deployment platform and an overview of a typical HPGe detector system.

2.1 HPGe SYSTEMS AND MEASUREMENTS

The RTIMP maintains a number of HPGe detectors. Each detector system consists of a high-purity germanium crystal, charge collection device, and preamplifier, all cooled by a liquid-nitrogen cryostat, all of which is mounted on a tripod of adjustable height. The preamplifier is connected to a multi-channel

analyzer (MCA), which converts the analog signals (voltage pulse height) from the detector into digitized data. The resultant energy spectrum is stored on a portable computer where it is analyzed to determine the activity concentration of gamma-emitting radionuclides in soil. A picture of a tripod-mounted HPGe detector is shown in Figure 2-1.

The HPGe detectors used at the FCP are EG&G ORTEC GAMMA-X® n-type, typically 80% efficient, low-background detectors with a thin beryllium window, giving a useful energy detection range of 3 keV to 10 MeV. The MCAs have 8192 channels of data storage with a typical gain of 0.375 KeV per channel. Spectral data from the MCAs are sent using LabView® software to a laptop computer, where it is analyzed using EGAS®, gamma spectrometry software provided by an independent contractor.

The success of gamma spectrometry as a quantitative analysis hinges on the fact that many radionuclides emit gamma rays with energies that are characteristic of those particular nuclides. Even if an isotope of interest does not emit usable gamma rays itself, gamma spectrometry may still be used as a quantitative analysis technique if radioactive daughters of the isotope of interest emit gamma rays that can be used for quantification. When this is the case, gamma spectrometry can provide valid results if the daughter isotope is in radioactive equilibrium with the isotope of interest. This is the case for the three primary isotopes of concern at the FCP: U-238, Th-232 and Ra-226. The energy of the gamma photons used to quantify the isotopes of concern at the FCP are given in Table 2-3, along with the daughter isotopes which emit them and the gamma photon abundance. Each isotope listed in the left-most column of Table 2-3 is assumed to be in secular equilibrium with the daughter isotopes listed beside it in the second column. Because Ra-226 is a unique case in which full equilibrium with its daughters is usually not established, special corrections (as described in section 5.6 of this manual) must be applied to Ra-226 data to generate valid results.

HPGe measurements are taken to satisfy many FCP requirements (Section 3.0), and each radionuclide of interest has a unique set of gamma photons that are used for quantification (Table 2-3). To achieve these measurement objectives, the HPGe instrument measures U-238, Th-232 and Ra-226 activity (Ra-226 corrections are described in Section 5.6) by assuming secular equilibrium with, respectively, thorium-234 and protactinium-234m; thallium-208 and actinium-228; and lead-214 and bismuth-214.

The user has control over four factors that affect HPGe measurements: the measurement location, detector height, data acquisition time, and the time of day and year of the measurement. Measurement location is

determined using approaches discussed in Section 3.0. Most HPGe measurements are performed with a detector height of 31 cm; but, in special cases, detector heights of 100 cm and 15 cm are used. Data acquisition time is usually 5 minutes. The time of day and year of the measurement may affect results due to diurnal or annual changes in environmental conditions, such as daily variation in the degree of atmospheric mixing of radon-222 (Rn-222) or seasonal variations in rainfall and snowfall.

2.1.1 HPGe Strengths and Limitations

Strengths

- HPGe provides quantitative data for a wide variety of gamma emitting isotopes in addition to the three primary contaminants of concern. These data exhibit a very high degree of precision, low minimum detectable activities, and good accuracy.
- HPGe can provide accurate and meaningful information on U-238, Th-232 and/or Ra-226 hot spot detection, confirmation and delineation, and uranium WAC exceedances (Section 3.0).
- An individual HPGe measurement provides characterization data on a significantly larger volume of soil than can be obtained by analysis of a single physical sample. The *in situ* characterization data are obtained more rapidly and at lower cost compared to data generated by a laboratory.
- Varying the HPGe detector height allows measurements to be made over a variety of viewing areas. This allows different sized areas to be examined quickly and also allows for boundary delineation. Additionally, multiple measurements at different detector heights at a given location may provide valuable information on the degree of homogeneity of the contaminant distribution.
- Variable fields of view (i.e., different viewing areas at different detector heights) more closely map contamination to evaluate clean-up criteria, relative to discrete samples (i.e., areas associated with hot spot criteria).
- As necessary, HPGe can provide 100 percent coverage of an area. This allows the identification of WAC and hot spot problems better than physical samples.
- HPGe allows measurements to be performed rapidly. A single measurement is obtained in approximately 5 minutes. However, other factors limit the number of measurements that can be made in a day. Refer to Section 4.3 for details.
- The availability of multiple HPGe detectors allows multiple systems working in tandem to quickly cover an area.
- Less than 24-hour turnaround times for data are easily achievable with the HPGe systems.
- HPGe data are amenable to storing, manipulating, and archiving electronically just as conventional analytical data are.
- *In situ* gamma spectrometry analyses cost significantly less than laboratory gamma spectrometry measurements, particularly when turnaround times are considered. It costs approximately $150 - $200 for an *in situ* gamma measurement with turnaround time of 24 hours or less, taking into account site preparation, QA/QC, instrument transport, and radiological constraints. The cost to obtain comparable laboratory analyses with a 30-day turnaround time is approximately $300 per sample, taking into account sampling, sample management activities, and analytical costs.

- Studies published in the scientific literature have demonstrated that the varying topography commonly encountered at the FCP is unlikely to cause a significant bias in the *in situ* HPGe measurements performed by the RTIMP.
- A wide variety of terrains may be measured. These include vertical sidewalls, trenches, pits, and sloping walls. The algorithms used by HPGe systems can be customized as necessary to achieve measurement objectives in a variety of terrains.
- It is possible to recognize when shine or interference from other radionuclides are adversely effecting *in situ* HPGe measurements because these detectors have very high resolution compared to NaI detectors. This fundamental property of HPGe detectors makes it possible to differentiate two radionuclides in the soil, provided their characteristic gamma emissions are more than 2 keV apart.
- HPGe systems can be used when the ground is frozen (if there is no snow cover and a moisture reading is available) and samplers cannot take core samples easily.
- Measurements are non-destructive and non-intrusive.

Limitations

- The measurements cannot be used for certification, as no promulgated methods or measurement acceptance criteria exist for *in situ* measurements such as those associated with contract laboratory program (CLP) or Solid Waste, Tracking No. 846 (SW846) protocols.
- Ra-226 measurements cannot be used without correction or adjustments for Rn-222 disequilibrium in surface soils. Also, when conditions (particularly in the morning) are conducive to the buildup of Rn-222 in near surface air and in surface soil, a separate radon monitor must be employed to provide information for Ra-226 correction algorithms. When practical, measurements should be made in the afternoon to avoid possible morning Rn-222 buildup.
- Individual measurements are hard to interpret in heterogeneous environments. This is particularly true when the scale of the heterogeneities is on the order of or less than 50 percent of the field of view at a given detector height.
- If used in small, confined areas, such as pits or trenches, correction factors may be needed to account for the unique geometries of the areas. (But measurements are conservative in that measurement results will be higher than actual concentrations when correction factors are not employed.)
- HPGe measurements cannot be made in rain or snow. Measurements must not be made after a heavy rainfall, when snow is on the ground, when the ground is saturated with water or when standing water occupies a significant portion of the field of view.
- A single soil moisture measurement within the field of view, as is current practice, might not be representative of the average moisture within the field of view.
- When making measurements in the vicinity of buildings or drums where radioactive material is stored, gamma radiation from the radioactive material might interfere with gamma radiation from radionuclides of interest in the soil. This "shine" might lead to elevated measurements (i.e., false positives).
- Only those radionuclides that emit gamma rays within the energy range of the HPGe system can be directly detected, and only if they are present within the top 10-15 cm of soil.

2.1.2 Guidance

- The strengths and limitations listed above for HPGe systems must be considered when writing PSPs, IRDPs, and certification design letters.
- HPGe and NaI systems complement each other. When used in tandem, the strength of the two systems together can exceed the sum of the strengths of the individual systems.
- When in doubt as to the correct usage of HPGe or NaI systems, consult the RTIMP group for advice.
- Ensure that all QC requirements specified in RTIMP-M-003, RTIMP Operations Manual, are met for the data quality level required for the measurement.
- Detector height and data acquisition time are a function of particular data objectives. Refer to Section 3.0 for details.

2.1.3 See Also

3.0 Use of *In Situ* Gamma Spectrometry Systems in the FCP Soil Remediation Program
4.5 Detector Field of View and Area Coverage
4.7 HPGe Data Acquisition Time
4.8 Trigger Levels
4.11 Surface Condition and Topographic Effects
4.6 HPGe Grid Configurations
4.12 Environmental Influences on *In situ* Gamma Spectrometry Data
4.13 Shine and Buried Sources
4.3 Time Required to Complete Scanning of a Remediation Area
5.0 Technical Topics

2.2 RTRAK SYSTEM AND MEASUREMENTS

The RTRAK system is comprised of a John Deere™ tractor, a 4-inch by 4-inch by 16-inch NaI crystal, photomultiplier tube and signal preamplifier (i.e., the detector components) that are housed in a padded high-density polyethylene tube, a multi-channel pulse height analyzer, a GPS unit, and a computer (Figure 2-2). A steel frame extending off the rear of the tractor is used to mount the detector at a height of 31 cm (1 foot) above the ground, and the long axis of the crystal is oriented perpendicular to the direction of travel. The GPS antenna is mounted on the tractor and the GPS receiver, DART and computer are housed within the cab of the tractor.

Detector signals are processed and stored in the MCA memory channels. A series of 512-channel gamma-ray spectra, each representing 4 seconds of elapsed clock time, are collected as the vehicle moves over the contaminated soil. The accumulated spectral data is transferred to the system computer where it is analyzed by EGAS, a gamma spectral analysis software package. All of these operations are controlled

by LabView® executable routines, which were developed for the FCP by staff of the Idaho National Engineering and Environmental Laboratory. The system computer transmits processed data via a wireless Ethernet® connection to a computer in a mobile van called the Field Operations Center (FOC) where data can be further processed to produce maps of radionuclide concentrations in the soil.

For nearly all applications, the RTRAK is used in a mobile mode to provide essentially complete coverage of an area, but it can be used in a static mode if longer counting times are desired for a particular location. The standard data-collection routine for the RTRAK is to move the detector over the ground at a speed of 1 mph and collect GPS coordinates and a gamma-photon spectrum every 4 seconds. In contrast to the HPGe system, NaI systems collect data in a "real time" mode, as opposed to a "live time" mode. That is, NaI-based systems are typically operated with the dead time compensation turned off so that each 4-second spectrum represents the same ground area coverage. For a 4-second count, the actual counting time is generally greater than 3.8 seconds (i.e., a small fraction of the 4-second count time is detector dead time, when no counts are recorded).

The RTRAK can be used to detect and quantify U-238, Th-232, and Ra-226 activity by assuming secular equilibrium with their respective daughters protactinium-234, thallium-208, and bismuth-214 (Table 2-4). However, the RTRAK system uses a NaI detector that has poor energy resolution (±50 keV) in comparison to the HPGe detectors (±2 keV). Consequently, NaI detectors cannot separate peaks that are within approximately 50 keV of each other, and gamma photons with energies near those of analytes of interest can result in interferences that affect the validity of an RTRAK result. All three analytes of interest for RTRAK applications (U-238, Th-232, Ra-226) can be affected by interfering gamma rays. The peak regions of interest for the isotopes of concern have been selected to minimize interference. The calibration methodology generates interference coefficients to account for the presence of interfering gamma rays. However, when the activity of one or more of the analytes is substantially higher than the others, the interference can result in inaccurate results for the smaller component, irrespective of the compensating factors embodied in the calibration equations. The gamma rays that interfere with the analytes of interest are summarized in Table 2-5.

Four factors can be varied to affect RTRAK measurements in the mobile mode: path followed, data acquisition time, the degree of overlap between adjacent passes, and the time of day and year the measurements are made. The path to be followed will be specified in general terms in the appropriate PSP, which considers the nature of the area to be surveyed and the intended application of the results (e.g., hot spot vs. above-WAC scan). Most often the path will consist of alternate back and forth passes.

Data acquisition time is 4 sec, but two 4-second spectra can be combined to form an 8-second spectrum if more counts in a specific region of the spectrum are needed to achieve a result below the specified action level. Overlap is typically 0.6 m (between adjacent passes, Figure 4-5). The time of day (for Ra-226) and time of year during which measurements are made may affect results due to changes in environmental conditions. Seasonal changes affect soil moisture profiles and thus add some uncertainty to moisture measurements and consequently to all moisture corrected measurements.

2.2.1 RTRAK Strengths and Limitations

Strengths

- The RTRAK is able to provide 100 percent coverage of most open areas in a short period of time (an acre may be measured in as little as two hours). Complete coverage provides the ability to identify zones that exceed 1) the On-Site Disposal Facility (OSDF) WAC for uranium, and 2) the U-238, Ra-226, and Th-232 hot spot criteria. Hot spot criteria are discussed in detail in Section 3.3 of this manual.
- The cost of RTRAK data is low relative to the large number of physical samples that would need to be collected and analyzed to achieve comparable coverage. Depending upon amount of site preparation, degree of overlap between passes, terrain considerations, and the radiological environment, RTRAK data cost between about $500 and $1,000 per acre. Assuming that one physical sample every 300-400 square feet is adequate to characterize an area, then 125 physical samples would need to be collected per acre. Sample collection, sample management office, and analytical costs total approximately $300 per sample (125 x $300 = $37,500 per acre). Therefore, RTRAK is about 37-75 times less expensive than physical samples on a per acre basis.
- RTRAK produces gross activity data that can be used to map general patterns of radioactivity in surface soil.
- RTRAK provides quantitative radionuclide concentration data (in the form of picocuries per gram) for U-238, Th-232, Ra-226, cesium-137, potassium-40 and other radionuclides. This allows calculation of average concentrations for a given area.
- RTRAK spatial resolution increases (the ability to distinguish differences between smaller areas) as speed decreases to zero, to a maximum resolution on the order of 10 to 17 m^2. That is, it is able to resolve heterogeneous contaminant distribution on a scale of 10 to 17 m^2 when stationary measurements are taken.
- RTRAK can detect WAC exceedances for total uranium with a 4-second measurement. Gross activity data may also be used to detect potential WAC exceedances.
- RTRAK can also reliably detect hot spots at three times the FRL for U-238 (when FRL is 82 mg/kg), Ra-226 and Th-232.
- In general, an area scan, data reduction, map preparation, and data QA/QC review can be completed within 24 hours. Preliminary results of the scan can be viewed as the data are being collected.
- RTRAK may be used when the ground is frozen (if snow cover is absent and a soil moisture reading can be obtained).

- RTRAK measurements are non-destructive and non-intrusive.
- RTRAK cab is air-conditioned, creating a more moderate operating environment for both equipment and personnel.

Limitations

- RTRAK cannot perform measurements in heavily wooded areas, in deep pits, or on sloping walls in which the slope is greater than 0.5:1. The RSS and Gator platforms are appropriate for this terrain (Sections 2.3 and 2.4), while the EMS is suited to deep excavation areas and trenches.
- In general, measurements performed with the RTRAK and the other NaI systems will have larger measurement uncertainties and higher minimum detectable concentrations than HPGe measurements. This is a consequence of the much shorter NaI count times – 4 seconds as compared to five minutes. However, a single 4-second measurement is sufficient to quantify Th-232 at FRL (1.5 pCi/g) and Ra-226 and total uranium at 1.25 times FRL (2.1 pCi/g and 103 mg/kg respectively).
- Low FRLs for total uranium (10 and 20 mg/kg, equivalent to 3.3 and 6.6 pCi/g U-238, respectively) exist in various locations at the FCP, and the NaI detectors are unable to measure to three times the FRL (10 and 20 pCi/g) unless moving measurements are aggregated or data are collected in a stationary mode. However, if stationary measurements are to be made, they are best performed with the HPGe systems.
- Care must be taken when aggregating measurements such that the size of the area represented by the aggregation is not significantly larger than the scale of the object of interest. Aggregation reduces spatial resolution, and consequently it is not a routine practice.
- Correction algorithms are needed to adjust Ra-226 measurements to compensate for Rn-222 disequilibrium in surface soil (Section 5.6). Propagated uncertainties resulting from the Rn-222 correction process contribute to a somewhat elevated Ra-226 MDC (about 1.25 times its FRL for an 4-second count).
- Gamma photons from nearby contamination sources that are not within the normal field of view of the detector may be recorded by the detector (referred to as shine). The shine may not be recognized as such and results will be biased high.
- RTRAK measurements cannot be made immediately after heavy rain, when snow is on the ground, when soil is saturated with water, or when standing water occupies a significant portion of the field of view.
- RTRAK only measures contamination in the uppermost layer of soil (approximately the top 10 - 15 cm).
- Because of the inherently poorer resolution of NaI detectors, RTRAK is restricted to measuring a limited number of gamma emitting radionuclides.
- The wheels, chassis and other components of this NaI platform may become contaminated when it is operated in an area with elevated contamination levels. The vehicle must be decontaminated when exiting a measurement area that is radiologically controlled. Decontamination may be a difficult and time-consuming process.
- Because of the size of the RTRAK, a single person cannot function as both driver and gamma spectrometry operator.
- Because of its weight, use of the RTRAK might by limited on soft surfaces.

2.2.2 Guidance

- For general survey applications of an acre or more, begin with RTRAK or one of the other mobile NaI systems (RSS or Gator, discussed below) and follow-up with HPGe measurements (Section 3.0).
- If a uranium WAC exceedance or a hot spot is detected with a NaI system, individual measurements with the HPGe system will be used to confirm and delineate the boundary of any such area.
- Total activity data (i.e. total gamma counts registered regardless of energy) are easy to obtain since they do not require processing of gamma ray spectra. However, these data are more difficult to interpret in that the total activity does not provide information on differences in spatial variations of individual radionuclides (Section 4.14).
- Refer to Section 5.2 and Table 2-5 to assess expected impacts of gamma photon interferences on *in situ* NaI measurement results.
- When in doubt as to the correct usage of NaI vs. HPGe systems, consult the RTIMP group.
- Prior to using any motorized platform, ensure the system is in proper working order.

2.2.3 See Also

3.0 Use of *In Situ* Gamma Systems in the FCP Soil Remediation Program
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
4.14 Interpretation of NaI Total Activity Data
4.12 Environmental Influences on *In Situ* Gamma Spectrometry Data
4.13 Shine and Buried Sources
4.15 Mapping Conventions
4.3 Time Required to Complete Scanning of a Remediation Area
5.4 Minimum Detectable Concentration or Activity
5.6 Radium-226 Corrections
5.7 Data Review and Validation
5.9 Quality Control Considerations for Field Measurements
5.10 Positioning and Surveying
5.11 Analysis of Uncertainties in HPGe and NaI Measurements

2.3 RADIATION SCANNING SYSTEM AND MEASUREMENTS

Some areas of the FCP site cannot be accessed with the RTRAK vehicle because of its size. To scan such areas for radionuclides, a 4-inch by 4-inch by 16-inch NaI detector, signal processing electronic modules, GPS, and computer-based multichannel pulse height analysis system have been mounted on a three-wheeled jogging stroller (Figure 2-3). All of this equipment, including the stroller, is called a Radiation Scanning System (RSS). Several RSS's are maintained and operated by the RTIMP group. The NaI detector, MCA, and GPS components are identical to those used in other NaI systems, regardless of the platform that deploys the components.

An RSS is pushed by hand and achieves portability by using very compact, battery-operated, MCA and GPS components that are connected to a portable laptop computer loaded with a multichannel analyzer emulator and a gamma spectrum acquisition program. Detector height is set at 31 cm (1 foot) above the surface and the operator pushes the system at a nominal speed of 1 mph while collecting a spectrum and GPS coordinates every 4 seconds. Data reduction is carried out in the manner described for the RTRAK, and information in Tables 2-2 and 2-4 apply to the RSS and all other NaI systems, except the nanoSPEC.

Aside from the size difference, two significant differences exist between the RSS and the RTRAK. First, the RSS computer and electronics are not in an enclosed, air-conditioned cab, like they are in the RTRAK, which has minor implications for cooling and for protecting the RSS equipment in the event of precipitation. Second, the long axis of the NaI detector is parallel to the direction of motion for the RSS system, whereas in the RTRAK the long axis of the NaI detector is perpendicular to the direction of motion.

The ninety-degree difference in NaI crystal orientation for RTRAK and RSS gave rise to the concern that these instruments might generate significantly different results if both instruments were used to scan the same area. A study was conducted to determine if this concern was valid. The results of that study are described in detail in Appendix C of the January 1999 RTRAK report. While it is true that the elongated shape of the NaI detectors (4 inches by 4 inches by 16 inches) gives rise to an elliptical field of view, the major axis of the ellipse is only about 7% larger than the minor axis. In other words, the field of view is nearly circular.

Before the calibration pad was built, the RSS was calibrated by performing stationary measurements at a series of field locations that were characterized with an HPGe detector. During these field calibrations, RSS readings were collected at both 0° and 90° detector orientations. RTRAK readings were also collected for comparison purposes. There was generally good agreement among the two RSS and the single RTRAK readings. In the few locations where there was poor agreement among the NaI detector readings, HPGe readings taken at two or three detector heights indicated that one or more radionuclides were not homogeneously distributed.

In addition to comparing stationary NaI readings taken at different crystal orientations, two separate comparisons of mobile NaI measurements collected at 0° and 90° crystal orientations were performed. In the first case, RSS followed right behind RTRAK as it was driven back and forth along the same path

twenty times, thus ensuring that the two detectors oriented at 90° to one another traversed exactly the same ground. This was done at the FCP in the Uranium in-Soils Integrated Demonstration (USID) Area, which was known to have homogeneously distributed contamination. In the second case, both RTRAK and RSS performed a full area scan of a portion of the Drum Baling Area (DBA). No attempt was made to ensure that the two detectors traversed exactly the same ground in the second comparison. The DBA was known to have higher levels of contamination than the USID Area, with the contamination being more heterogeneously distributed. In both tests, the ground scanned was split into segments and segment averages and standard deviations were compared. In the USID Area there was good agreement between RSS and RTRAK segment averages (% differences were 10% or less), with poorer agreement for U-238. The poorer agreement for U-238 in the USID Area was attributed to the low U-238 concentration in this area. The MDCs for the detectors were not low enough to reliably quantify U-238. In the DBA percent differences for segment averages were less than 20% for all three isotopes. These tests lead to the overall conclusion that RTRAK and RSS mobile measurements yielded comparable results despite the different crystal orientations.

2.3.1 RSS Strengths and Limitations

Strengths

- An RSS can make measurements in wooded terrains and uneven or sloped terrains where the RTRAK cannot maneuver.
- Like the RTRAK, data collection with the RSS is far less costly than analyzing physical samples to achieve comparable areal coverage.
- Unlike the RTRAK, an RSS can make measurements under relatively wet soil conditions. Because it is considerably lighter than RTRAK it is less likely to sink into wet soil.
- RSS is highly maneuverable and can easily make a very dense grid of overlapping measurements over a small area to help delineate boundaries.
- The ease of maneuverability and operability of an RSS allows moving measurements to be augmented with stationery measurements at longer count times should the need arise to improve both precision and accuracy of the measurement.
- RSS is easy to mobilize and demobilize, thereby increasing cost effectiveness and productivity. This is a consideration for small areas (< 0.25 acre).
- RSS is easier to decontaminate than the RTRAK of GATOR. Moving it from one contaminated measurement area to another should be easier and faster.
- RSS is low maintenance and requires no fuel.

Limitations

- RSS may be difficult to push at a constant and predetermined speed. Terrain must not have deep ruts or holes if a constant 1 mph traverse is to be maintained.
- Because the electronics and computer are not enclosed in an air-conditioned cab, RSS electronics may be more susceptible to temperature effects than RTRAK electronics. High temperatures may create problems with computer operations, thereby affecting data acquisition, manipulation, and storage.
- RTRAK is more practical than RSS for large, flat areas.
- RSS may be difficult to push and operate in areas with high grass.
- The wheels, chassis and other components of this NaI platform may become contaminated when it is operated in an area with elevated contamination levels. The vehicle must be decontaminated when exiting a measurement area that is radiologically controlled. Decontamination may be a difficult and time-consuming process, although the smaller wheels and chassis of the RSS should make it easier to decontaminate than the other NaI vehicles.
- RSS operators are exposed to the weather, while RTRAK has an air-conditioned cab.

2.3.2 Guidance

- For general survey applications of an acre or more, begin with RSS or one of the other mobile NaI systems and follow-up with HPGe measurements (Section 3.0).
- If a uranium WAC exceedance or a hot spot is detected with a NaI system, individual measurements with the HPGe system will be used to confirm and delineate the boundary of any such area.
- Use RSS in areas that are not suitable for RTRAK or Gator. Such areas include those on the order of an acre or less in size, areas with trees or other closely spaced obstacles, and areas with soft or sloping terrain. For general survey applications of larger areas, begin with RTRAK (or Gator, discussed below) and follow-up with HPGe measurements (Section 3.0).
- Refer to Section 2.2.2 (RTRAK) for general guidance on the use of NaI systems.
- When in doubt as to the correct usage of NaI vs. HPGe systems, consult the RTIMP group.

2.3.3 See Also

3.0 Use of *In Situ* Gamma Systems in the FCP Soil Remediation Program
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
4.14 Interpretation of NaI Total Activity Data
4.12 Environmental Influences on *In situ* Gamma Spectrometry Data
4.13 Shine and Buried Sources
4.3 Time Required to Complete Scanning of a Remediation Area
4.15 Mapping Conventions
5.4 Minimum Detectable Concentrations
5.6 Radium-226 Corrections
5.7 Data Review and Validation
5.9 Quality Control Considerations for Field Measurements
5.10 Positioning and Surveying
5.11 Analysis of Uncertainties in HPGe and NaI Measurements

2.4 GATOR SYSTEM AND MEASUREMENTS

The Gator is a mobile NaI system that was built to fill the gap between the large and heavy RTRAK and the small, manually-pushed RSS's. Like the RTRAK, it can be used for rapid coverage of large flat areas; but it has the advantage that it can be driven in tighter places and on steeper terrain than the RTRAK. It can be used any place RTRAK can be used, and in many places that the RSS systems cover. All the NaI systems perform the functions of surveying general patterns of U-238, Th-232 and Ra-226 distribution, detecting above-WAC uranium levels in soil, and detecting hot spots during precertification scans.

The Gator platform is a John Deere®, diesel powered, six wheeled, utility vehicle with a 4-inch by 4-inch by 16-inch NaI detector that is mounted on the vehicle. Two different detector-mounting systems have been devised for the Gator. A sodium iodide detector can be mounted on the front of the vehicle using a bracket specially designed for this purpose (Figure 2-4). A detector can also be mounted on a specially designed trailer and pulled behind the Gator. The detector height is 31 cm above the ground in both mounting configurations. When the detector is mounted on the front of the vehicle, the long detector axis is perpendicular to the dissection of travel, whereas when it is trailer-mounted, the long detector axis is parallel to the direction of motion. The system electronics are identical to those described for other NaI platforms and they are housed in the cab of the vehicle, although the cab provides less climate control than the RTRAK.

Gator performs surveys in the standard operating mode of 1 mph with repeated acquisition of 4-second gamma spectra. It typically surveys in a back-and-forth pattern with 0.6 m overlap on the scanned footprint. The performance characteristics of the detector and signal processing system, including precision, and minimum detectable activity, are similar to those for the RTRAK and RSS systems. It is subject to the same potential gamma photon interferences as the other NaI platforms.

2.4.1 Gator Strengths and Limitations

Strengths

- Ability to survey in tighter spaces, over softer ground, and on steeper terrain than the RTRAK
- The motorized Gator can maintain more uniform speed and is less fatiguing than the operator-pushed RSS
- The Gator is easier to deploy than RTRAK and possesses all the strengths of the RTRAK, except the air-conditioned cab to cool laptop computer and system electronics.

Limitations

- System electronics may be affected by high temperatures on hot days
- Operators are not protected from heat as they are with RTRAK.
- The wheels, chassis and other components of this NaI platform may become contaminated when it is operated in an area with elevated contamination levels. The vehicle must be decontaminated when exiting a measurement area that is radiologically controlled. Decontamination may be a difficult and time-consuming process.

2.4.2 Guidance

- For general survey applications of an acre or more, begin with GATOR or one of the other mobile NaI systems and follow-up with HPGe measurements (Section 3.0).
- If a uranium WAC exceedance or a hot spot is detected with a NaI system, individual measurements with the HPGe system will be used to confirm and delineate the boundary of any such area.
- The Gator may be used to survey both small and large areas. It may be used anywhere RTRAK is used and most places RSS is used.
- Refer to Sec 2.2.2 (RTRAK) for general guidance on use of NaI systems.
- When in doubt as to the correct usage of NaI vs. HPGe systems, consult the RTIMP group.

2.4.3 See Also

3.0 Use of *In Situ* Gamma Systems in the FCP Soil Remediation Program
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
4.14 Interpretation of NaI Total Activity Data
4.12 Environmental Influences on *In situ* Gamma Spectrometry Data
4.13 Shine and Buried Sources
4.3 Time Required to Complete Scanning of a Remediation Area
4.15 Mapping Conventions
5.4 Minimum Detectable Concentrations
5.6 Radium-226 Corrections
5.7 Data Review and Validation
5.9 Quality Control Considerations for Field Measurements
5.10 Positioning and Surveying
5.11 Analysis of Uncertainties in HPGe and NaI Measurements

2.5 EXCAVATION MONITORING SYSTEM AND MEASUREMENTS

The Excavation Monitoring System (EMS) is a self-contained gamma detection system that is capable of deploying the NaI and HPGe detectors that are in routine use at the FCP (Figure 2-5). It is attached to a standard excavator and includes a self-righting vertical mast, with a detector mount that can accommodate either an HPGe or NaI detector. The vertical mast is suspended from a horizontal platform that is coupled to the arm of the excavator. It holds an on-board computer, GPS, a laser-based location measurement

systems, and data transmission equipment. The GPS and laser-based position measurement systems provide a more precise means of measuring the location at which each gamma spectral measurement is performed, including the vertical coordinate in addition to X and Y horizontal coordinates. Other major components of the system include excavator cab and support van computers, data processing software, and display screens.

The EMS is used in non-standard survey situations that cannot be handled by the other platforms, for example, surveys of pits, trenches, mounds, vertical surfaces, soft or wet ground, or locations where access is difficult or unsafe. A 2-foot or 4-foot extension rod may be attached between the lower end of the mast assembly and the detector to enable the detector to reach the bottom of deeper excavations. In "reach in" situations, the EMS protects workers and reduces their potential exposure.

Real-time gamma measurements can be made in several modes, including stationary measurements at a prescribed detector height and mobile scanning measurements at a prescribed detector height and scanning speed. Either gross activity or spectrometric measurements can be collected in any of these modes. All measurements, stationary or mobile, are tagged with detector location (X, Y and Z coordinates) as determined by the onboard GPS or laser-based systems. The movement of the EMS-mounted detector over the survey area is tracked using either the GPS or a laser-based tracking system that traces detector location on display screens in the excavator cab and in the support van.

The EMS is intended for use in the same phases of the FCP soil remediation program as the other real-time platforms, namely in excavation predesign, excavation support, and precertification. The main survey activities associated with these program phases are delineation of excavation boundaries, identification of soil with concentrations of uranium above the OSDF WAC, identification of hot spots, and checking residual contaminant levels to confirm the effectiveness of cleanup actions. The use and detailed description of the EMS is discussed in a report entitled Development and Deployment of the Excavation Monitoring System (DOE 2002a, hereafter called the EMS Manual).

EMS Description and Operation

The main component of the EMS, which is mounted on the arm of a standard excavator, is called the excavator tool (ET). A drawing of the ET (Figure 2-6) identifies the major components of the device. The ET stands approximately 72 inches tall, by 32 inches wide, by 50 inches deep, with the detector mounted, but excluding the available 2-foot or 4-foot detector mount extensions. The entire unit weighs roughly 200 pounds, while the removable detector assembly weighs roughly 46 pounds. Other major components of the EMS include computers and displays located in the excavator cab and, if needed, in the support van.

An HPGe or NaI detector is suspended at the end of the mast assembly. The signal processing modules, antennae and other electronic equipment are housed on the horizontal platform, located at the top of the mast assembly. Each detector assembly is equipped with four ultrasonic proximity sensors, which provide collision-warning signals when the detector approaches an excavation wall or other nearby object. Each detector assembly is also equipped with a laser rangefinder capable of measuring the distance to the surface being surveyed. The laser rangefinder functions as a collision warning system and also allows positioning of the detector at the appropriate height above the surface being surveyed.

Three computers are used in the EMS, one mounted on the ET, one in the excavator cab, and one in the support van (if needed). The ET-mounted computer performs important signal processing and data transmission functions associated with the collection of spectral and position data from detectors and sensors on the ET. The integrated data are transmitted via a wireless Ethernet connection to the other two computers, which display and record the data as needed. Display panels in the excavator cab and support van provide the information to the excavator operator and EMS operators needed to position the device and interpret gamma readings as they are made.

Information on the excavator cab display includes a scaled coverage plot similar to that available on other NaI systems, a numerical reading of latitude and longitude from the GPS positioning system, and of detector-to-ground offset as determined by the detector-mounted laser range finder. Also displayed are four lateral hazard-warning lights activated when the ET approaches a lateral object within a preset limit as determined from readings from the four laterally mounted ultrasonic sensors on the ET. This information is used primarily to protect the detectors from collisions during scanning.

A support van computer can be used to control data acquisition functions of the devices mounted on the excavator tool, mainly the gamma detectors and positioning systems. System software is capable of controlling and acquiring data from both NaI and HPGe detectors. The system can be operated in either static or mobile scanning modes. The menu-driven software that controls the system allows recording the physical tool configuration and orientation with respect to the excavator. Gamma spectra are displayed as they accumulate over time, and EGAS gamma spectrum analysis software, when loaded, can analyze spectral data from either NaI or HPGe detectors to produce a calibrated energy spectrum. The software can further analyze such spectra to determine the identities and activities of the radionuclides corresponding to the recorded spectral peaks.

Excavation characterization support with the EMS will be carried out in a rapid turnaround fashion as is currently done with the other *in situ* gamma spectrometry systems. Knowledgeable personnel in an EMS support van can perform data reduction, review, and mapping as needed. Excavation maps based on EMS data can be available within hours of data collection. It is possible for characterization and excavation activities to be conducted at the same time in different parts of an excavation area.

Geometry Corrections

In situ gamma measurements are influenced by measurement geometry. Detectors calibrated to measure radionuclide concentrations in surface soils on flat ground will give a somewhat higher or lower result for the same soil concentration when the measurement geometry (i.e., the soil surface contributing to the reading) is not flat. The magnitude of the effect of non-flat terrain on measurement results can be modeled from geometric considerations; correction factors for various non-flat geometries have been computed and are presented in an EML report (Miller 1999). The application of these correction factors to EMS detector readings is discussed further in the EMS Manual (DOE 2002a).

For nearly all cases that will be encountered in FCP excavations, the effects due to non-flat terrain are such that results will be biased high. That is, measurements are conservative. In cases where such a conservative bias leads to unnecessary excavation, corrections for non-flat geometry may be applied to obtain more accurate measurements. Figure 2-7 shows the procedure for making geometric corrections. As shown in the figure, readings below the action levels will not require correction because any such correction would only reduce the reading further because there is a positive bias for all below-grade readings. Conversely, all readings in excess of twice action levels would indicate an above-action level condition even if geometry corrections were made, because the maximum correction for geometry is a factor of two. Only readings between the action level and twice the action level warrant correction for geometry.

The EML-603 report (Miller 1999) serves as the basis of geometry corrections that will be applied to *in situ* gamma measurements made at the FCP, including those made with EMS. The FCP uses an industry standard method of calibrating HPGe detectors. The calibration method makes use of the fact that *in situ* gamma measurements above flat ground involve cylindrical symmetry. Under EML-603 guidance, corrections for non-flat terrain require the determination of the solid angle subtended at the detector by the ground surface contributing gamma flux to the measurement. The geometric correction factor, which is used to compensate for the fact that the gamma flux is not originating from flat ground, is computed by dividing the solid angle for the non-flat terrain by the solid angle for flat ground. Dividing the "flat

ground" result by the geometric correction factor, which is usually a number between 1 and 2, provides a result that is appropriately adjusted to account for the non-flat terrain.

To determine the solid angle subtended by the non-flat measurement, some simple information on the geometry is needed, as described in EML-603. The information includes H, the depth of the excavation; h, the height of the detector from the floor of the excavation; and X, the horizontal distance from detector to the wall of the excavation. The values of H, h, and X are used to determine the angle from the detector to the excavation top edge, known as the horizon angle, θ. The solid angle, Ω, can then be determined using equations in EML-603 for various pit shapes. Refer to the EMS Manual and EML-603 for instructions on making corrections for geometry. Access the available software utility or perform manual calculations to compute correction factors for specific locations.

2.5.1 EMS Strengths and Limitations

Strengths

- Use of the EMS can greatly reduce hazards to workers and worker exposure when working in inaccessible areas or in contamination areas.
- EMS can be used in areas that cannot be surveyed by any other platform. In particular, it can be used in deep excavations and in pits and trenches.
- EMS can deploy both NaI and HPGe detectors.
- EMS can perform all of the measurement functions of the other real-time platforms.
- The EMS excavator can operate in soft soils.
- EMS facilitates a continuous excavation process.
- EMS has an air-conditioned cab.

Limitations

- The large excavator that supports the EMS requires wide and high clearance access to survey areas.
- Particular care must be taken to protect the detector when the EMS is used, as a collision with the walls or floor of an excavation could destroy the detector. (The HPGe is not provided with physical protection so as to preserve its calibration integrity.)
- The tracks, chassis and other components of this NaI platform may become contaminated when it is operated in an area with elevated contamination levels. The vehicle must be decontaminated when exiting a measurement area that is radiologically controlled. Decontamination may be a difficult and time-consuming process.
- A person with special training is required to operate the EMS.
- Geometric corrections for measurements in non-flat terrain may be required (as for any real-time platform).

2.5.2 Guidance

- Refer to all appropriate reference manuals when deploying the EMS (or any *in situ* gamma system). These include the EMS Manual (DOE 2002a), the SEP (DOE 1998), Calibration of NaI *In Situ* Gamma Spectrometry Systems (DOE 2001), *In Situ* Gamma Spectrometry Addendum to the SCQ (Procedure FD-1000, Appendix H, DOE 2002c), EML-603 (Miller 1999), the EMS Acceptance Testing Plan and Report (DOE 2002a), and this report.
- Coordinate excavation and characterization activities. Consider whether or not the EMS needs to enter the excavation area. It may be possible for the EMS to accomplish survey goals by merely reaching into an area from outside the boundary.
- Determine which detector, NaI or HPGe, will be required for various purposes. See the reference documents mentioned.
- Determine the need and the procedure for making geometry corrections in non-flat terrain. Follow the EMS Manual and EML-603. Calculate corrections manually or use the available software application.
- Refer to Section 2.1 for guidance on use of HPGe detector systems and Section 2.2 (RTRAK) for guidance on use of NaI detector systems.

2.5.3 See Also

3.0 Use of *In Situ* Gamma Systems in the FCP Soil Remediation Program
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
4.14 Interpretation of NaI Total Activity Data
4.11 Surface Condition and Topographic Effects
4.12 Environmental Influences on *In situ* Gamma Spectrometry Data
4.13 Shine and Buried Sources
4.3 Time Required to Complete Scanning of a Remediation Area
4.15 Mapping Conventions
5.4 Minimum Detectable Concentrations
5.6 Radium-226 Corrections
5.7 Data Review and Validation
5.9 Quality Control Considerations for Field Measurements
5.10 Positioning and Surveying
5.11 Analysis of Uncertainties in HPGe and NaI Measurements

2.6 nanoSPEC AND MEASUREMENTS

The nanoSPEC is the newest tool to be adopted by the RTIMP. It is significantly different from the other NaI tools, and has only limited specialized uses. The nanoSPEC is a commercially available self-contained gamma spectrometry system. It consists of multichannel analyzer (MCA), amplifier, and high voltage power supply built into the NaI detector photomuliplier tube (PMT) base. The RTIMP uses a 4-inch diameter by 4-inch thick (4"x4") cylindrical NaI detector with the nanoSPEC PMT base, rather than the smaller sized NaI crystals that are usually sold with this unit (Figures 2-8a and 2-8b). The

commercial nanoSPEC unit has limited on-board data storage capacity and spectral analysis capability. However, the RTIMP has linked the nanoSPEC to a personal computer, which greatly increases the storage capacity and enables EGAS to be used for spectral analysis. EGAS is the software that is used to analyze all the other *in situ* spectra collected at Fernald.

When scanning soil in posted high-contamination zones, like that expected in Area 6, the FCP waste pits, there is a concern that the wheels and other components of the RTIMP NaI scanning vehicles may become highly contaminated. The mobile NaI vehicles are generally decontaminated on a daily basis in order to remove them from contaminated remediation areas for post-operational QC checks and proper storage. When exiting from high-contamination areas, the decontamination process can be difficult and time consuming. To avoid frequent repetition of a potentially lengthy decontamination process, the hand-held nanoSPEC NaI detector has been placed into service for initial scans within high-contamination areas. The detector can be covered with thin plastic wrap to prevent it from becoming contaminated, making it easier to release it from a contaminated area.

The most significant difference between the nanoSPEC and the other NaI detectors used by the RTIMP is the size of the crystal. The nanoSPEC uses a 4"x4" cylindrical crystal instead of the 4-inch by 4-inch by 16-inch (4"x4"x16") log crystal used in the other NaI-based systems. Because of its smaller volume, the 4"x4" crystal will be less efficient than the 4"x4"x16" detector. In other words, for the same activity level in the soil, a 4"x4" detector will register fewer counts than a 4"x4"x16" detector over the same time interval. This translates into lower sensitivity, greater relative measurement uncertainty and higher detection limits for the 4"x4" nanoSPEC detector. Because of this, its use will be limited to situations where high levels of contamination are expected.

Instead of being mounted to a vehicle, the nanoSPEC is carried by an analyst, with the detector suspended 31 cm above the ground. Four-second spectra are collected as the analyst walks back and forth across the contaminated area at a speed of one mile per hour (1.5 feet per second). At the present time, any location measurement data, such as GPS-based or manual survey measurements, must be manually linked to gamma spectral data to determine the location where each spectrum was acquired. Assuming that personnel safety issues can be appropriately resolved, the hand-held NaI detector can be used on any horizontal, sloped or vertical surface where other RTIMP NaI detectors, including the EMS, would normally be deployed. The nanoSPEC uses the customary gamma rays to quantify U-238, Ra-226 and Th-232 (Table 2-4), and it can be rapidly deployed with little risk of becoming contaminated. Thus, it is a good tool to help decide if an area is too contaminated for other RTIMP NaI detectors.

When deployed in high-contamination areas, the lower sensitivity (i.e., higher MDCs and lower trigger level) of the 4"x4" NaI detector is inconsequential, as the calibration process has demonstrated that the nanoSPEC has adequate sensitivity to detect areas of elevated contamination. After a pre-scan has been completed, and the most highly contaminated soils have been removed, the RTIMP then proceeds with a normal NaI scan with one of the 4"x4"x16" NaI detectors as though no prior scanning had been done. Therefore, the pre-scan with the nanoSPEC is done to avoid contaminating the 4"x4"x16" NaI mobile scanning systems, and not to replace the customary data set that all stakeholders receive.

2.6.1 nanoSPEC Strengths and Limitations

Strengths

- Using the nanoSPEC to pre-scan an area suspected of being highly contaminated will avoid the time-consuming decontamination process associated with using another NaI system to complete the scan.
- The nanoSPEC is easily transported and can be deployed rapidly.
- There is little risk of contaminating the nanoSPEC detector, since no part of the nanoSPEC system comes in contact with contaminated surfaces. Also, the system can easily be covered with thin plastic wrap to prevent it from becoming contaminated when it is used under dusty conditions.
- Assuming personnel safety issues can be resolved and low MDCs are not needed, the nanoSPEC can be used in areas that are inaccessible by other NaI platforms.

Limitations

- The nanoSPEC has higher detection limits and a lower WAC trigger level than the 4"x4"x16" NaI detectors, and its use is primarily limited to "pre-scans" in areas suspected of being highly contaminated.
- Because the nanoSPEC will be used to perform walkover surveys in high-contamination areas, where anti-contamination clothing and other personal protective equipment is required, scanning sizable areas could be time consuming.
- Safety issues, such as heat stress or personnel radiation exposure, may limit the time spent in contaminated areas when performing nanoSPEC surveys.
- After completing a pre-scan nanoSPEC survey to guide removal of the most highly contaminated material, the area must still undergo a full area scan by a 4"x4"x16" NaI system.

2.6.2 Guidance

- Use the nanoSPEC in situations where there is a concern that the other NaI platforms may become highly contaminated because of elevated contaminant levels in the area to be scanned.
- Use the nanoSPEC to identify above WAC materials to be excavated before commencing a normal scan with one of the 4"x4"x16" NaI detectors. Treat any area with a nanoSPEC result greater than or equal to 728 mg/kg total uranium as being above WAC.

- In very dusty environments, cover the nanoSPEC with thin plastic wrap to prevent it from being contaminated.
- The nanoSPEC has higher MDCs than the FCP 4"x4"x16" NaI detectors. Although it is capable of detecting elevated contaminant levels it should not be used to replace full area scans with the larger detectors because of its lower sensitivity.
- At the present time, GPS location information cannot automatically be merged with spectral measurements from the nanoSPEC. This function must be performed manually.

2.6.3 See Also

3.0 Use of *In Situ* Gamma Systems in the FCP Soil Remediation Program
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
4.14 Interpretation of NaI Total Activity Data
4.11 Surface Condition and Topographic Effects
4.12 Environmental Influences on *In situ* Gamma Spectrometry Data
4.13 Shine and Buried Sources
4.15 Mapping Conventions
5.4 Minimum Detectable Concentrations
5.6 Radium-226 Corrections
5.7 Data Review and Validation
5.9 Quality Control Considerations for Field Measurements
5.10 Positioning and Surveying

TABLE 2-1
USE OF HPGe SYSTEMS AS A FUNCTION OF DATA QUALITY LEVEL

HPGe System Measurement Objective	Analyte	ASL*	Does HPGe meet ASL Criteria for Usage?
Predesign Investigations			
Develop a general sense of contamination patterns	Total Uranium, Th-232, Ra-226	A	Yes
Identify WAC exceedance areas	Total Uranium	B	Yes
Delineate excavation footprint of above-WAC soil	Total Uranium	B	Yes
Determine the lateral extent of below-WAC (for total uranium) but above-FRL material, taking ALARA into consideration.	Total Uranium, Th-232, Ra-226	A	Yes
Soil Excavation and Segregation			
Excavation of Above-WAC Soil			
Verify NaI measurements on the horizontal extent of above-WAC material	Total Uranium	B	Yes
Identify above-WAC material in situations where NaI cannot be Used	Total Uranium	B	Yes
Precertification			
Confirm and evaluate potential residual hot spots identified by NaI systems	Total Uranium, Th-232, Ra-226	B	Yes
Verify removal of hot spots after excavation	Total Uranium, Th-232, Ra-226	B	Yes

*There are no specific QC requirements for ASL A in the SCQ.

TABLE 2-2
USE OF NaI SYSTEMS AS A FUNCTION OF DATA QUALITY LEVEL

NaI System Measurement Objective	Analyte	ASL*	Can NaI Achieve Measurement Objective?
Predesign Investigations			
Develop a general sense of contamination patterns and radioactivity patterns	Total Activity, Total Uranium, Th-232, Ra-226	A	Yes. Total activity can distinguish between low and high levels of contamination. Total activity cannot discriminate between isotopic differences.
Identify potential WAC exceedance areas	Total Activity, Total Uranium	A	Yes for total uranium. Total activity should be confirmed by other measurement approaches.
Soil Excavation and Segregation			
Excavation of Above-WAC Soil			
Assess horizontal and vertical removal of above-WAC material as excavation proceeds	Total Activity, Total Uranium	A	Yes. Total activity should be confirmed by other measurement approaches.
Survey design-based floor of excavation to identify potential above-WAC areas	Total Activity, Total Uranium	A	Yes. Total activity should be confirmed by other measurement approaches.
Precertification			
Evaluate patterns of residual radioactivity on design-based excavation floor	Total Activity, Total Uranium, Th-232, Ra-226	A	Yes, to delineate high areas from low areas, but more subtle differences may not be resolvable.
Identify potential hot spots during precertification scans	Total Uranium, Th-232	A	Yes, but total uranium cannot be used to identify hot spots for FRLs of 10 or 20 mg/kg.

*There are no specific QC requirements for ASL A in the SCQ.

TABLE 2-3
GAMMA PHOTONS USED IN HPGe MEASUREMENTS TO QUANTIFY URANIUM-238, THORIUM-232, AND RADIUM-226

Radionuclide of Interest	Radionuclides Measured*	Gamma Photon Energy (keV)	Gamma Photon Abundance (%)
Uranium-238	Thorium-234	63.2	3.9
	Thorium-234	92.6	5.41
	Protactinium-234m	1001.0	0.845
Thorium-232***	Actinium-228	338.4	12.01
	Thallium-208	583.1	30.96**
	Actinium-228	911.1	29.0
Radium-226	Lead-214	351.9	37.6
	Bismuth-214	609.3	47.0
	Bismuth-214	1120.4	17.0

* A weighted average activity for the isotope of interest is calculated where the weighting factor is the inverse of the square of the counting error on the measured isotope--exactly as specified for gamma spectrometry of physical samples.

** Includes 0.359 branching ratio from decay of bismuth-212.

*** The radionuclides measured for determining thorium-232 are similar to those specified for gamma spectrometry analysis of thorium-232 physical samples by analytical laboratories, with one exception. The gamma photon at 969.1 keV from actinium-228 is also specified for use in physical samples. Exclusion of actinium-228 (969.1 keV) leads to a result slightly higher (hence, slightly more conservative) than if it were incorporated into the weighted-average calculation.

TABLE 2-4
GAMMA PHOTONS USED FOR SODIUM IODIDE MEASUREMENTS

Radionuclide of Interest	Radionuclide Measured	Gamma Photon Energy (keV)	Gamma Photon Abundance (%)	Signal Window (keV)
Uranium-238	Protactinium-234m	1001.0	0.845	941 - 1040
Thorium-232	Thallium-208	2614.6	35.9*	2404 – 2825
Radium-226	Bismuth-214	1764.5	15.4	1649 – 1918

* Includes 0.359 branching ratio from decay of bismuth-212

TABLE 2-5
SUMMARY OF GAMMA PHOTON INTERFERENCES RELEVANT TO SODIUM IODIDE MEASUREMENTS

Radionuclide of Interest	Radionuclide Measured	Gamma Photon Energy (keV)	Radionuclide Emitting Interfering Gamma Photon	Energy of Interfering Gamma Photon (keV)	Effect of Interference
Thorium-232	Thallium-208	2614.6	Bismuth-214 (from Radium-226 decay)	2204 2293 2448	Bias Thorium-232 low
Radium-226	Bismuth-214	1764.5	Actinium-228 (from Thorium-232 decay)	1664-1666 (4 gammas) 1887	Bias Radium-226 low
Uranium-238	Protactinium-234m	1001.0	Thallium-208 (from Thorium-232 decay)	982	Bias Uranium-238 high
				860 1093	Bias Uranium-238 low
			Actinium-228 (from Thorium-232 decay)	969	Bias Uranium-238 high
				944-1033 (7 gammas)	Bias Uranium-238 high
				835 840 1065 1095	Bias Uranium-238 low
			Bisumth-214 (from Radium-226 decay)	964	Bias Uranium-238 high
				1069 1120	Bias Uranium-238 low
			Lead-214 (from Radium-226 decay)	839	Bias Uranium-238 low

Figure 2-1. A Tripid-Mounted HPGe System

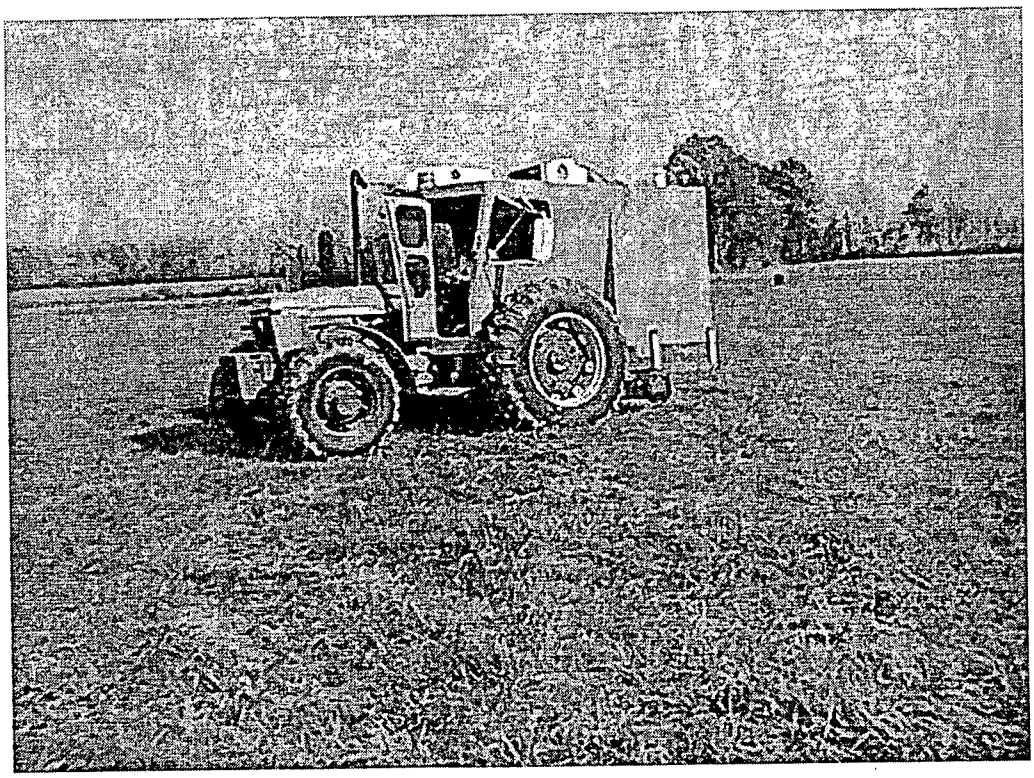


Figure 2-2. The RTRAK Mobile NaI System

Figure 2-3. An RSS Mobile NaI System

Figure 2-4. The Gator Mobile NaI System

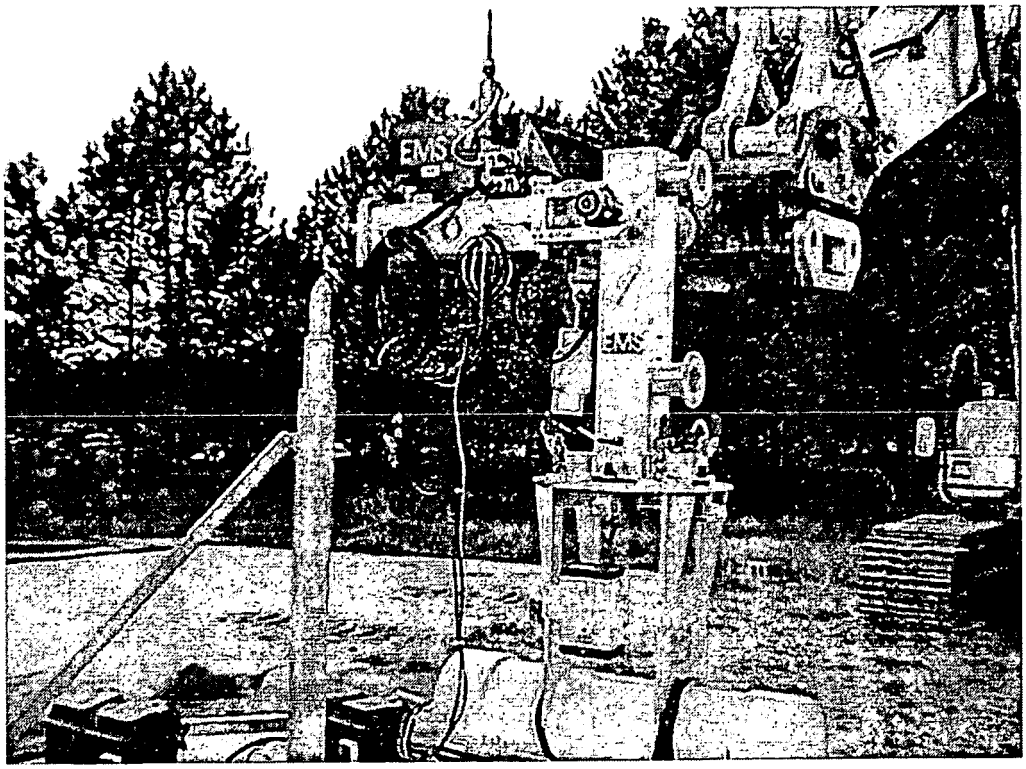


Figure 2-5a. The Excavator-Mounted EMS Equipped with a NaI Detector *(close-up view)*

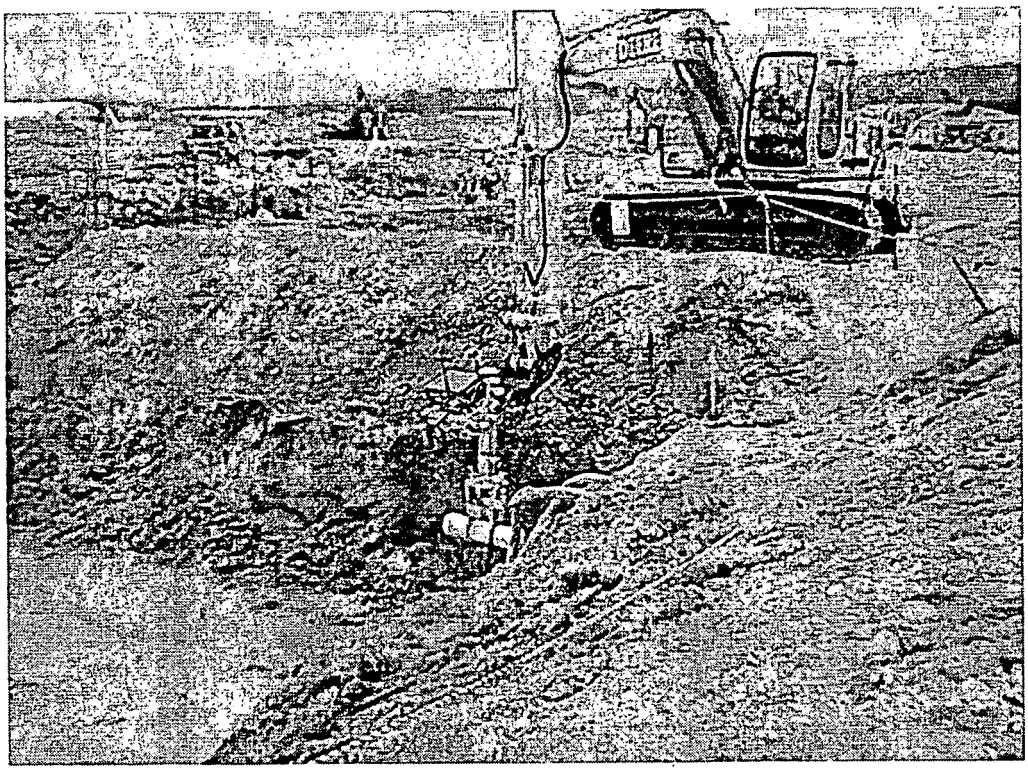


Figure 2-5b. The Excavator-Mounted EMS Equipped with a NaI Detector

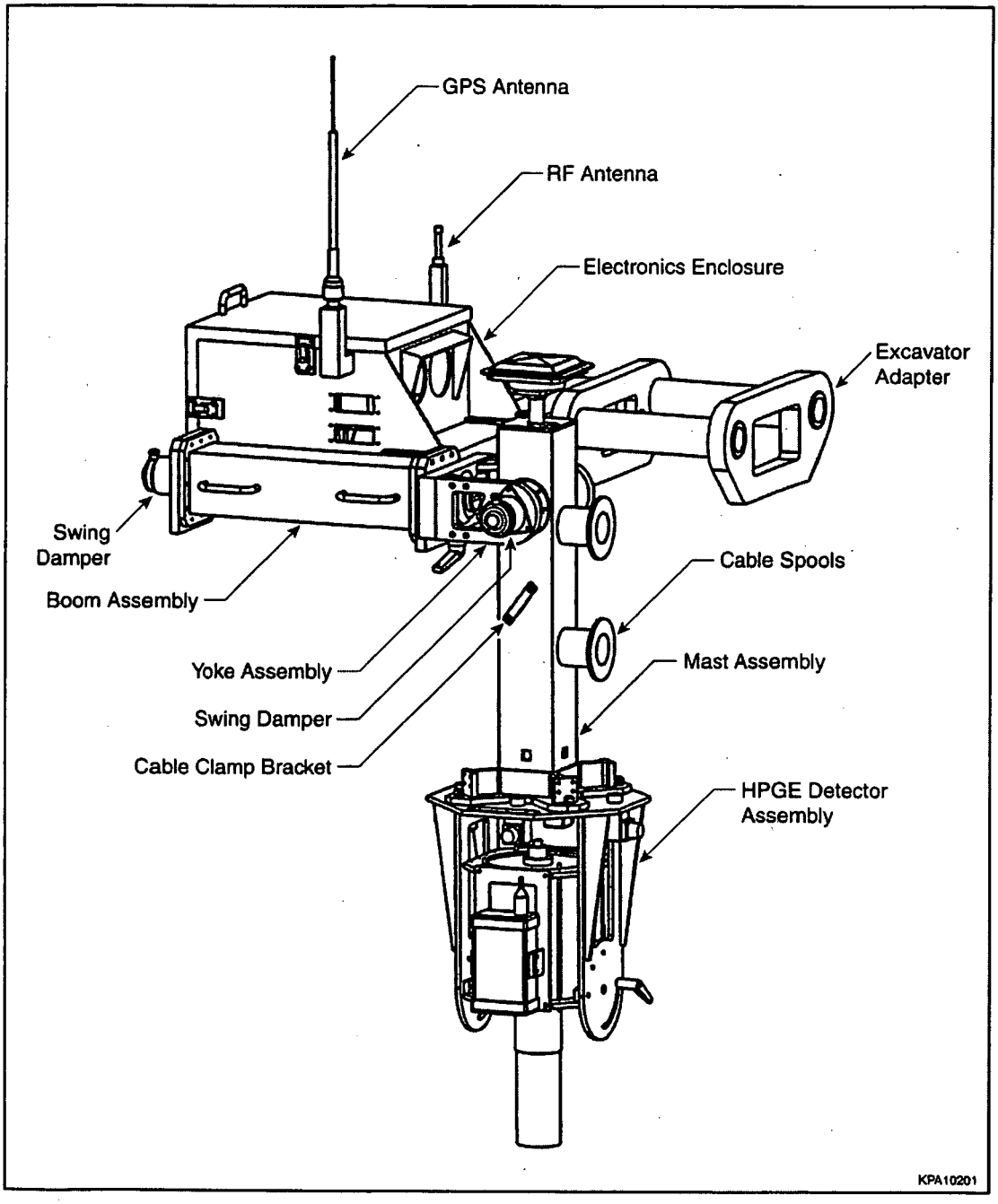


Figure 2-6. The EMS Excavator Tool with HPGe Detector

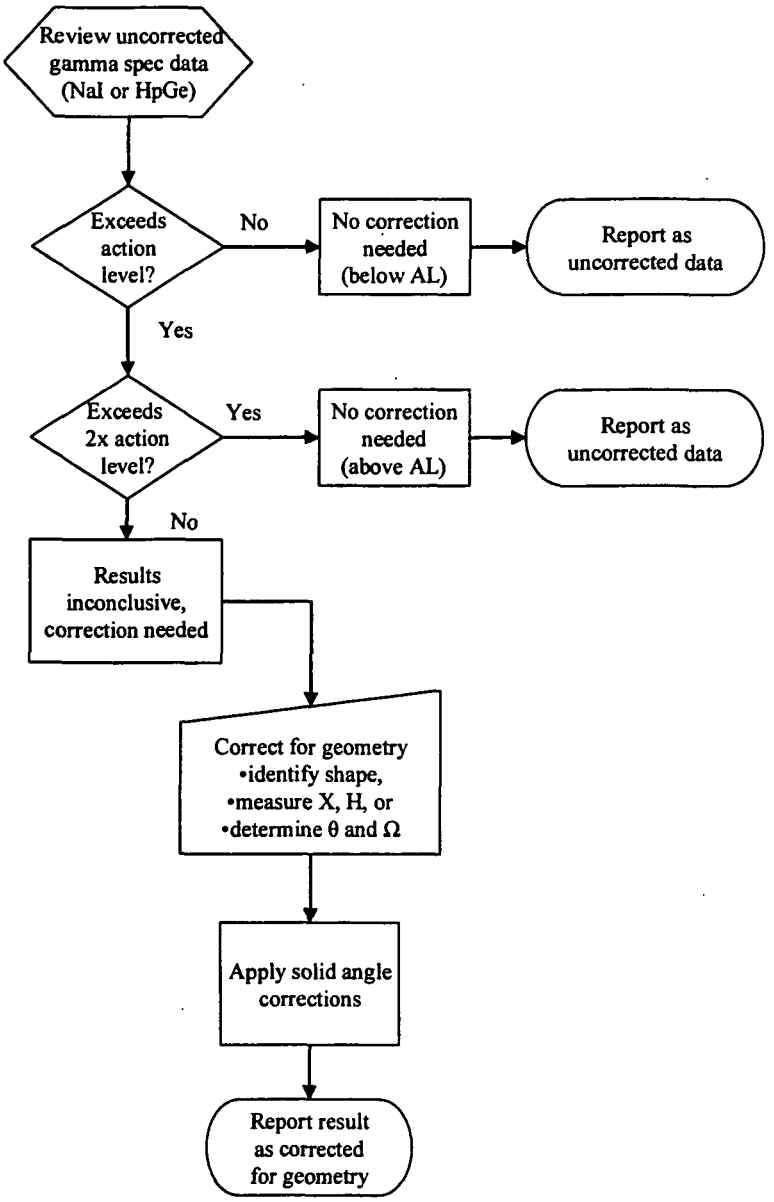


Figure 2-7. Procedure for Application of Geometric Corrections for Non-Flat Terrain

Figure 2-8a The nanoSPEC NaI System for Pre-Scanning Contaminated Areas

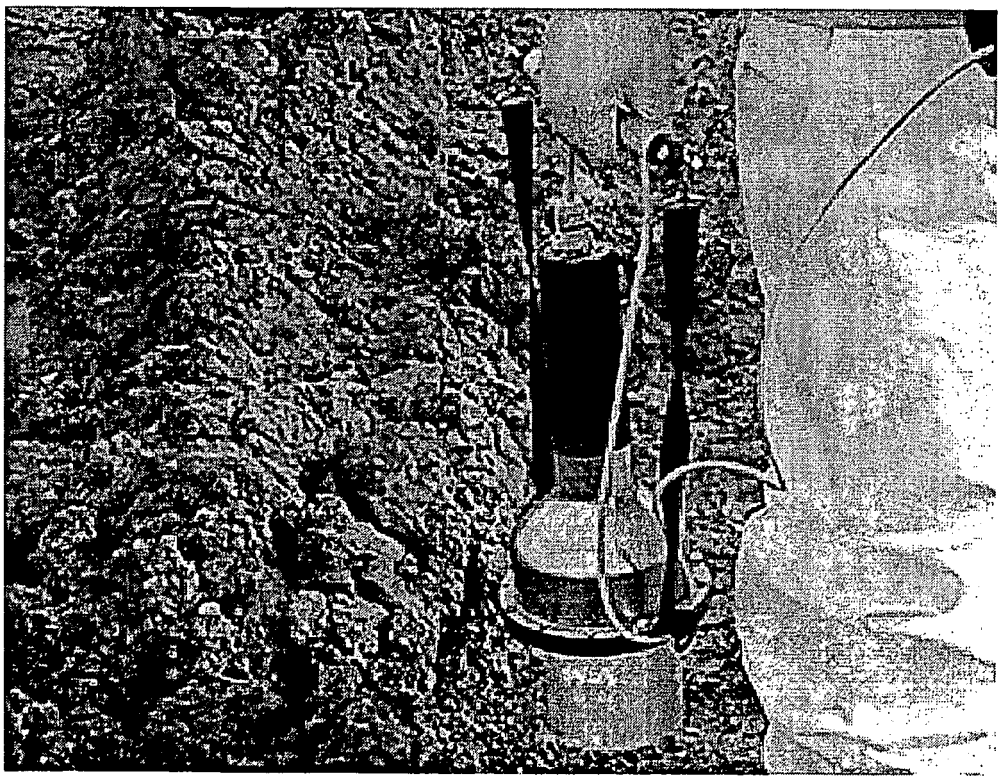


Figure 2-8b The nanoSPEC System (*close-up View)*

3.0 USE OF *IN SITU* GAMMA SPECTROMETRY SYSTEMS IN THE FCP SOIL REMEDIATION PROGRAM

The purpose of this section is to provide a description of the operational protocols that govern the use of *in situ* gamma spectrometry instruments during soil remediation activities. More detail on general investigation approaches and issues related to individual areas are provided in the SEP. Area-specific issues are discussed in the SEP and the relevant IRDPs as needed. Details on specific approaches are also provided in area-specific and activity-specific PSPs.

Use of HPGe and NaI systems provides essential measurement data in support of remediation operations at the FCP. As noted in Figure 3-1, these operations fall into four general categories: predesign activities, soil excavation and segregation activities, precertification activities, and certification activities. Investigation protocols and *in situ* measurements support each of these four general areas of soil remediation.

3.1 PREDESIGN INVESTIGATIONS

In many remediation areas, data generated from remedial investigation (RI) activities are not sufficiently comprehensive to prepare detailed engineering designs and excavation drawings; therefore, additional radiological surveys and sampling programs must be implemented to collect additional needed data. Real-time, field-deployable instruments have the capability to satisfy a portion of these additional data needs, and their use will be integrated with discrete sampling and laboratory analysis to maintain a comprehensive characterization program during the remedial design process.

The objectives of predesign investigations are: 1) to estimate the extent of soil that is contaminated at levels above the FRLs or above the ALARA goal of 50 mg/kg total uranium; and 2) to delineate the extent of soil contaminated with uranium above the 1,030 mg/kg WAC for the OSDF. The overall predesign investigation strategy is to combine soil characterization data obtained from physical samples with supplemental data generated from *in situ* gamma spectrometry measurements to establish the volume of contaminated soil that must be excavated. Figure 3-2 summarizes the general predesign investigation process.

Table 3-1 summarizes the deployment protocols for real-time measurements during the predesign investigation, which are performed to evaluate the extent of uranium, thorium and/or radium contamination and whether uranium contamination is present in soil at levels that exceed the OSDF WAC. Phase I measurements are performed to assess the extent and level of uranium, thorium and

radium contamination. Phase II measurements are performed only if Phase I measurements indicate the potential for above-WAC levels of uranium.

Phase I measurements are made with either NaI or HPGe systems (Table 3-1). The decision on which system to use is based on terrain and equipment accessibility and availability. In general, NaI systems will be used for Phase I measurements to obtain rapid and approximately 100 percent coverage of an area, if possible. The main exception to the use of NaI systems is forested terrain, where HPGe systems would be deployed for Phase I measurements. If the Phase I measurements indicate the potential for above-WAC levels of uranium (total uranium greater than 875 mg/kg for NaI and total uranium greater than 400 mg/kg for HPGe measurement at a height of 100 cm; Sections 4.8 and 4.9), then Phase II measurements are performed to confirm the presence and extent of above-WAC uranium contamination. The action level for Phase I HPGe measurements was set lower than the NaI action level to provide assurance that a WAC exceedance area that is smaller than the 100 cm HPGe measurement field of view would not be missed. Because each HPGe measurement represents a weighted average concentration over the entire field of view, measurement of a 1.5-meter radius hot spot with a uranium concentration of 1030 mg/kg, and no uranium in the soil outside this radius, will yield a uranium concentration of approximately 400 mg/kg (Section 4.9).

Phase II measurements are performed with HPGe systems at a height of 31 cm, with the trigger level for above-WAC uranium contamination set at 928 mg/kg for a five minute measurement (Table 3-1). The measurements are taken at locations identified by Phase I measurements as exceeding the above-WAC action level for uranium. If a Phase II measurement exceeds a total uranium concentration of 928 mg/kg, the measurement area is considered to contain above-WAC levels of uranium and additional HPGe measurements are performed to determine the extent of the WAC exceedance. After the HPGe shots have bounded the areal extent of above-WAC contamination, the information is provided to the characterization group so they can develop a sampling plan to investigate the depth of the contamination.

3.1.1 Detection of General Patterns of Contamination

The initial objective of predesign investigations is to gain a good understanding of general patterns of surface contamination. Mapping the general patterns of surface contamination will provide the approximate areal extent of excavation and allow the sampling teams to focus on obtaining subsurface soil samples from the most contaminated areas. NaI data will be processed and plotted on maps to show areas with U-238, Th-232 and Ra-226 contamination that are below and above levels that correspond to

three times the FRL (the hotspot criteria), or above the MDCs for NaI systems. Activity contours at higher levels can also be mapped from NaI data. The interpretation of real-time data should be done in light of process knowledge of former plant operations and within the context of a conceptual physical model. For example, air deposition of particulates would distribute contamination uniformly over a broad surface, while spills and leaks of liquids would have little lateral dispersion, but might penetrate quite deep into soil. Any soil excavation or fill activities in an area would have a tendency to mix soil, perhaps driving surface contamination to greater depth, dispersing it laterally, or transporting it to another area. Considering applicable physical models of contaminant distribution along with available data should improve the interpretation of real-time data.

3.1.1.1 Maps for Illustrating Surface Contamination

Maps are provided by the RTIMP group to show the extent of surface contamination. Four maps are generated for NaI measurements: U-238 activity or total uranium concentration, Th-232 activity, Ra-226 activity and total activity (i.e. gamma counts per second, regardless of energy). For HPGe systems, three maps are generated to summarize the specific isotope activities, but total activity maps are not generated. The area covered by each measurement is depicted by a colored symbol (squares for NaI measurements and circles for HPGe shots) that is coded to the activity level. Color-coded activity levels are plotted as squares or circles on a base map to allow the user of the map to quickly identify contaminated areas that exceed three times the U-238, Th-232 and Ra-226 FRLs and/or the WAC for uranium. A detailed discussion of mapping conventions and map examples are presented in Section 4.15.

3.1.2 Estimation of Above-FRL Excavation Boundary

When performing scans to determine the boundaries of areas that exceed FRLs, those planning and performing the measurements must be cognizant of the MDCs for the instruments being used to ensure that the MDCs are below the applicable FRLs. (A more detailed discussion on detection limits is provided in Section 5.4 of this report.) Although MDC values for the RTIMP NaI systems show nominal variation from system to system, approximate values for a four-second count time are as follows: total uranium MDC – 100 mg/kg, Th-232 MDC – 0.8 pCi/g and Ra-226 MDC – 1.7 pCi/g. So, while these systems can detect Th-232 at or below its FRL of 1.5 pCi/g with a four-second count, their ability to detect FRL levels for uranium (82 mg/kg) and Ra-226 (1.7 pCi/g) is marginal, at best. Because of the limited detection capabilities of the NaI systems when they are deployed to collect four-second spectra, a combination of NaI and HPGe measurements will be made to estimate the lateral extent of above-FRL surface contamination. Normally, one of the NaI systems will survey the entire area in question to identify general patterns of U-238, Th-232 and Ra-226 contamination, with follow-up HPGe measurements at the locations of the

highest isotopic and total activity results. If the HPGe results confirm that the highest NaI isotopic or total activity result was indeed above FRL, HPGe follow-up measurements will continue at the next highest NaI reading. This process will continue until the HPGe results drop below the applicable isotopic FRL. If time permits and there is a need to map the surface extent of U-238, Th-232 and Ra-226 contamination in more detail, HPGe systems alone can be used to estimate the above-FRL boundary with greater accuracy. Any of the RTIMP HPGe systems are capable of detecting FRL levels of U-238, Th-232 and Ra-226 when any or all of these isotopes are present in the soil (Section 5.4.1). An illustration of the above-FRL delineation process is provided in Figure 3-3.

3.1.3 Above-WAC Detection, Confirmation and Delineation

Detection of uranium concentrations above the established WAC for the OSDF is a key objective of the RTIMP. The measurement approach (Table 3-1) involves detection of soil with above-WAC concentrations of uranium during Phase I measurements with NaI or HPGe systems, followed by confirmation and delineation with HPGe during Phase II measurements.

3.1.3.1 Detection

Detection of above-WAC concentrations of uranium with the NaI systems can be achieved when the system is operated with a scanning speed of 1 mile per hour and an acquisition time of 4 seconds. If a single 4-second measurement exceeds the minimum action level (i.e. the WAC trigger level) of 875 mg/kg for U, or an HPGe measurement at a height of 100 cm exceeds 400 mg/kg for uranium, then soil with elevated uranium concentrations must undergo Phase II measurements to confirm the Phase I results (Table 3-1). If above-WAC concentrations of uranium have been detected on the basis of historic physical samples, those areas should be examined with Phase II HPGe measurements to confirm that the historic contamination is still present.

3.1.3.2 Confirmation

Confirmation of above-WAC concentrations of uranium will be obtained using HPGe measurements collected at a detector height of 31 cm and for a counting time of 5 min. Measurements will be made at Phase I locations that exceeded WAC trigger levels. The measurement location may be adjusted in the field using a hand-held instrument to determine the location of maximum activity. If a Phase II measurement exceeds the HPGe WAC trigger level of 928 mg/kg then additional HPGe measurements will be performed to delineate the extent of the above-WAC contamination. When Phase II measurements are below the HPGe total uranium trigger level of 928 mg/kg, the HPGe results may still be used to delineate a hot spot (i.e., three times the FRL for U-238, Th-232 or Ra-226). If above-WAC

concentrations of uranium were detected on the basis of results from historic physical samples, Phase II measurements should be carried out at the locations where the physical samples were taken to confirm the presence of above-WAC contamination.

3.1.3.3 Delineation

If above-WAC uranium contamination is confirmed by Phase II measurements, then additional HPGe measurements are needed to delineate the boundaries of above-WAC soil. For delineation, additional Phase II HPGe measurements will be made (Table 3-1) until the extent of the above-WAC contamination is bounded. Definition of the vertical extent of the above-WAC soil will require the collection of soil samples from borings. An example of the delineation process is illustrated on Figure 3-4.

3.1.4 Predesign PSP Overview

The following section summarizes the use of real-time systems during predesign and discusses a number of considerations that should be addressed in the preparation of PSPs for predesign work. Predesign data are collected using real-time instruments and physical samples to define the lateral and vertical extent of contamination. A PSP will contain key information on the identification labels for each real-time measurement and provide historical data and information on the areas that are to be measured with the real-time instruments. Activities during predesign that may involve the use of real-time systems include:

- Determine general patterns of surface contamination
- Estimate above-FRL contamination boundary
- Delineate above-WAC levels of uranium
- Prepare maps of surface contamination.

Specific real-time measurements may include the following:

- Conduct scans of surface soil with NaI systems to detect above-WAC uranium
- Perform NaI scans to estimate hot spots (3*FRL for U-238, Th-232, and Ra-226)
- Use HPGe measurements to delineate surface soil that has above-WAC uranium and estimate boundaries of above-FRL areas of U-238, Th-232 and Ra-226.

Questions that should be considered in the preparation of PSPs may include the following:

- What organizations will be involved in predesign activities with regard to the use of real-time data (e.g., Characterization, WAO, Construction, etc.)?
- What documents, procedures, methods and standards apply to various activities?
- Which real-time systems will be used to survey the various areas?
- How accessible is the area, with respect to physical mobility and GPS signal?
- What are the applicable uranium FRLs for the affected areas?

- What measurement numbering system will be used for NaI and HPGe data?
- What routine QA/QC procedures and measurements are required?
- What maps are required?
- What safety and health provisions must be made to protect field crews?
- What analytical support level (ASL) is required for the real time measurements?
- What are the requirements for data management?

3.1.5 Guidance

- Predesign data should be interpreted within the framework of a conceptual model that considers process knowledge and historic contamination records for the area of interest.
- Maps can be prepared from data generated by NaI and HPGe measurements to provide a visual image of contamination patterns.
- Data gaps should be identified for determining contaminant distributions, including identifying locations where Geoprobe corings are needed.
- NaI systems can be used to define the extent of surface contamination that corresponds to hot spot levels (i.e., 3*FRL) for uranium (82 mg/kg FRL only), Th-232, and Ra-226.
- HPGe measurements can detect U-238, Th-232 and Ra-226 at levels that correspond to their respective FRLs, and these measurements may be taken if a more accurate estimate of the FRL boundary is needed.
- Soil that exceeds the OSDF WAC for uranium can be identified using NaI (31-cm height) and HPGe (100-cm height) systems during Phase I measurements. The action levels that indicate potential above-WAC uranium contamination are 875 mg/kg for NaI measurements and 400 mg/kg for HPGe measurements. Any detector used must be capable of detecting uranium at concentrations equal to the corresponding action level.
- For Phase II HPGe measurements (31-cm height), a uranium WAC trigger level of 928 mg/kg (dry weight) is used for a 5-minute count time. Confirmation of above-WAC uranium levels necessitates additional measurements to delineate the extent of above-WAC contamination.

3.1.6 See Also

2.0 *In Situ* Gamma Systems Operated at the FCP
3.1.2 Estimation of Above-FRL Excavation Boundary
3.1.3 Above-WAC Detection, Confirmation and Delineation
4.5 Detector Field of View and Area Coverage
4.6 HPGe Grid Configurations
4.7 Data Acquisition Time
4.8 Trigger Levels
4.9 Detection of Above-WAC Uranium Contamination
4.14 Interpretation of NaI Total Activity Data
4.15 Mapping Conventions
5.4 Minimum Detectable Concentration

3.2 SOIL EXCAVATION AND SEGREGATION

The overall analytical objective for excavation control is to obtain real-time data on U-238 activity in soil exposed on fresh excavation surfaces. This data needs to be provided to construction personnel during the excavation process to ensure that any area identified as above-WAC with respect to uranium contamination is segregated from below-WAC soil and placed at the designated staging area for off-site disposal. Figure 3-5 depicts the general soil excavation and disposal process at the FCP.

Table 3-2 summarizes the deployment protocol for real-time measurements during excavation, which are performed to determine whether uranium contamination is present in soil at levels that exceed the OSDF-WAC. Phase I measurements are performed to screen the soil for potential above-WAC uranium contamination, and Phases II and III are executed only if Phase I measurements indicate the potential for above-WAC levels of uranium.

Phase I measurements are made with the NaI or HPGe systems (Table 3-2), and the decision on which system to use is based on accessibility and terrain. In general, NaI systems will be used for Phase I measurements to obtain rapid and approximately 100 percent coverage of an area, if possible. However, HPGe systems can be deployed for Phase I measurements if NaI systems cannot traverse the terrain. If the Phase I measurements indicate the potential for above-WAC levels of uranium (total uranium greater than 875 mg/kg for NaI and total uranium greater than 400 mg/kg for HPGe; Sections 4.8.1 and 4.8.2), then Phase II measurements are performed to confirm the presence and extent of above-WAC uranium contamination. In Phase I, the HPGe systems have a lower action level than NaI detectors for above-WAC uranium levels because the HPGe measurements are carried out at a height of 100 cm. The greater HPGe detecter height results in the detector seeing a diminished photon flux from a given, fixed area of above-WAC contamination (i.e., dilution occurs when measurements are made at 100 cm rather than 31 cm). The 400 mg/kg action level for HPGe at 100 cm corresponds approximately to a contaminant level of 1,030 mg/kg in a circular area having a radius of approximately 1.5 meters. This radius is not to be confused with the radius associated with the field of view seen by the detector, which is 6 meters when the HPGe detector height is 100 cm.

Phase II measurements are performed with HPGe systems at a height of 31 cm, with the trigger level for above-WAC uranium contamination set at 928 mg/kg for five-minute measurements (Table 3-2). The measurements are taken at Phase I locations where measurements exceed the above-WAC action level for uranium. The measurement location may be adjusted in the field using a hand-held instrument to determine the location of maximum activity. If a Phase II measurement exceeds a uranium dry weight

concentration of 928 mg/kg, the measurement area is considered to contain above-WAC levels of uranium and additional HPGe measurements are performed to determine the areal extent of the contamination. After the HPGe shots have bounded the above-WAC contamination, the information is provided to the construction manager and characterization group and the above-WAC soil is removed and staged for off-site disposal.

Phase III measurements (refer to Table 3-2) are usually conducted with NaI systems to verify that the above-WAC soil has been removed from the active excavation. However, these verification measurements may be carried out with HPGe systems, depending on equipment availability and/or terrain conditions. If any of the Phase III measurement results exceeds the applicable uranium WAC trigger level (875 mg/kg for NaI, 400 mg/kg for 100-cm HPGe or 928 mg/kg for 31-cm HPGe measurements; Sections 4.8.1 and 4.8.2), then Phase II measurements are performed again to confirm the presence and extent of above-WAC uranium contamination still remaining. When Phase III measurements show that there are no uranium WAC trigger level exceedances remaining, normal excavation activities will commence.

3.2.1 Above-WAC Excavation

Above-WAC soil may be identified prior to the start of excavation in an area or during the course of excavation. Once identified, the above-WAC material is removed and segregated as part of the excavation operation. Identification may be made through continuous visual inspection of uncovered areas, from physical samples or by radiological surveys using NaI or HPGe systems on each newly exposed soil surface. Excavation maps for above-WAC material can typically be generated by the end of the day for use the next day (see Section 4.15). Above-WAC soils or other materials are removed using conventional excavation equipment. Small volumes of above-WAC soil may be removed using hand shovels. After materials have been removed, the remaining footprint must be verified to be free of additional above-WAC material.

Verification of the removal of above-WAC soil, referred to as Phase III measurements, will normally be performed using the NaI or HPGe systems. However, removal of a small volume of material (i.e., where the surface area of the material in question is less than 1 m^2) may be verified using hand held friskers (Section 4.10), where a reading below 200,000 dpm would indicate the absence of above-WAC material. The nanoSPEC could also fulfill this function, with the added benefit that it can also provide spectrometric information. In this situation, a measurement below the nanoSPEC WAC trigger level of 728 mg/kg total uranium would indicate the absence of above-WAC material.

3.2.2 Excavation Control for Lifts

Excavation of soil takes place in lifts, with each lift being 3 to 4 feet thick. Excavation control is required on each lift to identify potential above-WAC uranium contamination on newly exposed soil surfaces. After a lift is removed, the area will be surveyed using the protocol in Table 3-2 and, if definition of the vertical extent of above-WAC soil is needed, physical samples can be collected and analyzed. Definition of the horizontal extent of above-WAC soil (i.e., Phase II confirmation and delineation) can be accomplished with HPGe measurements.

3.2.3 Soil Excavation PSP Overview

The following section summarizes the use of real-time systems during soil excavation and discusses a number of considerations that should be addressed in the preparation of PSPs for excavation control. In general, material prohibited from the OSDF (e.g., process residue) is identified by visual monitoring and removed prior to performing the NaI or HPGe measurements. Activities that may involve the use of real-time systems include the following:

- Identifying non-visible above-WAC materials on lift surfaces
- Confirming, delineating, mapping, and verifying the removal of above-WAC material
- Confirming the removal of visible contamination.

Specific real-time measurement activities may include the following:

- Performing NaI or HPGe surveys to detect above-WAC materials
- Confirming and delineating above-WAC materials using HPGe
- Preparing real-time excavation maps for above-WAC materials
- Performing NaI or HPGe surveys on the footprints of removed visible residues or other items prohibited from disposition in the OSDF that might have associated contamination.

Questions that should be considered in the preparation of PSPs might include the following:

- What organizations would be involved in executing the PSP?
- What is the excavation and characterization control process (Figure 3-6)?
- What documents, procedures, methods and standards apply to various activities (Figure 3-7)?
- What real-time systems will be used to survey the various areas?
- What is the physical and GPS accessibility of the areas?
- What ASL level is required for measurements?
- What numbering system will be used for NaI and HPGe measurements?
- What areas, if any, are of concern for Th-230?
- What routine QA/QC procedures are required?
- What field QC measurements are needed?
- What maps are required?
- What mapping van functions are required?
- What safety and health provisions must be made to protect field crews?
- What data management arrangements must be made?

3.2.4 Guidance

- Each lift is scanned with NaI or HPGe systems to screen for above-WAC levels of uranium.
- For Phase I and Phase III measurements, use a WAC action level for total uranium of 875 mg/kg for NaI and either 400 mg/kg (1-meter detector height) or 928 mg/kg (31-cm detector height) for HPGe measurements.
- If above-WAC uranium trigger levels are exceeded during Phase I measurements, the above-WAC zone must be confirmed and delineated (Phase II) using HPGe detectors.
- For Phase II HPGe measurements, use a WAC trigger of 928 mg/kg (dry weight) . This applies to 5-minute measurements at a detector height of 31 cm.
- Use a WAC trigger of 200,000 dpm when using beta/gamma friskers to determine the boundaries or verify the removal of small areas (less than 1 square meter) of above-WAC material.
- Use a uranium WAC trigger level of 728 mg/kg when using the nanoSPEC to determine the boundaries or verify the removal of small areas (less than 1 square meter) of above-WAC material.

3.2.5 See Also

2.0 *In Situ* Gamma Systems Operated at the FCP
3.1.3 Above-WAC Detection, Confirmation and Delineation
4.5 Detector Field of View and Area Coverage
4.6 HPGe Grid Configurations
4.8 Trigger Levels
4.9 Detection of Above-WAC Uranium Contamination
4.10 Use of Hand-Held Survey Meters

3.3 PRECERTIFICATION INVESTIGATIONS

The purpose of precertification is to obtain a high level of confidence that U-238, Th-232 and Ra-226 are less than their FRLs and the area is ready for certification. Therefore, NaI and HPGe measurements must be performed to identify potential hot spots for these isotopes. Hot spots are defined as localized areas where the U-238, Th-232 or Ra-226 concentrations exceed three times the applicable FRL. Figure 3-8 illustrates general precertification activities, and the RTIMP precertification protocol is summarized in Table 3-3.

3.3.1 Hot Spot Evaluation

As noted in Table 3-3, evaluation of each hot spot is carried out as a phased investigation. Phase I is preliminary detection of the hot spot; Phase II is confirmation and delineation of the hot spot and Phase III is verification of the removal of the hot spot. Figure 3-9 summarizes the hot spot criteria and the remediation implementation strategy. Each of these phases is discussed in more detail in the following sections.

When there is spectral evidence of elevated levels of Ra-226, *in situ* measurement results must be radon corrected before deciding if the Ra-226 concentration is above or below the hotspot criterion. The radon correction process is discussed in detail in Section 5.6 of this report. Normally, both NaI and HPGe *in situ* data have the laboratory radon correction automatically applied by the spectral data analysis software. A radon monitor must be deployed if time-of-day radon corrections are also needed. Both types of radon corrections, the laboratory correction and the time-of-day correction, must be applied to Phase II or Phase III *in situ* measurements before hotspot decisions are made.

3.3.1.1 Hotspot Detection

Phase I measurements (hotspot detection) are made with either NaI or HPGe systems (Table 3-3). The decision regarding which system to use is based on equipment availability and terrain accessibility. In general, NaI systems will be used for Phase I measurements, if possible, in order to obtain approximately 100 percent coverage of an area in a reasonably short time. However, HPGe systems can be deployed for Phase I measurements if NaI systems cannot traverse the terrain.

When NaI systems are used for Phase I measurements, each batch file (potentially containing hundreds to thousands of 4-second spectra) is screened to determine if hot spots (3xFRL for U-238, Th-232; and/or Ra-226) are present. If hot spots are present, the locations are identified and Phase IIa measurements are carried out at each hot spot. When no hot spots are found, the location with highest total activity is identified, and this location is evaluated with a Phase IIa measurement.

When HPGe detectors are used to perform Phase I measurements, 5-minute spectra are collected at a detector height of 100 cm. If results indicate the presence of U-238, Th-232 and/or Ra-226 greater than 3xFRL, the locations are identified and Phase IIb measurements are performed with the HPGe systems.

All of the RTIMP NaI and HPGe detectors are capable of detecting 3*FRL hotspots under normal operating conditions when the size of the hotspot is at least as large as the field of view of the detector being used. (In fact, all of the RTIMP HPGe detectors and some of the NaI detectors are capable of detecting isotopic concentrations equal to, and sometimes less than, the FRLs for the respective isotopes of concern. The detection limits of the RTIMP HPGe and NaI detectors are discussed more fully in Section 5.4 of this report.)

The ability to detect a hotspot is strongly dependent on the size of the hotspot, as well as its activity. If a small hotspot is surrounded by soil with little or no radioactive contamination, a measurement with either a NaI or an HPGe detector will not yield the true concentration in the central hotspot because any *in situ* measurement represents a weighted average of all the soil activity within the detector field of view. Furthermore, since the soil near the center contributes relatively more toward the weighted average than the soil near the outer edge of the detector field of view, the location of the hotspot within the field of view also heavily influences the result. Only when the hotspot is approximately the same size as the detector field of view will the measurement result approximate the true activity in the soil. This is true because the "calibration coefficient" used to convert counts per second registered by the detector to picocuries per gram for an isotope-specific spectral region of interest is not strictly appropriate unless the measurement geometry is an infinite half-space containing soil that is uniformly contaminated with respect to both position on the surface and depth within the soil.

When thinking about detecting smaller and smaller hotspots, the detection limits of the instrumentation must be considered. As the size of a hotspot shrinks, even though the radionuclide concentration remains constant, an *in situ* detector will give lower and lower results. When the hotspot shrinks to a certain size, it will no longer be detectable. This concept is illustrated in Figure 3-10, which displays the calculated response of a detector to three different hotspot activity levels as a function of the radius of the hotspots. In all cases, it is assumed that the detector is 31 cm above a uranium hotspot that is centered directly beneath the detector, and that there is no soil contamination outside the boundary of the hotspot. The detector response was computed for successively smaller and smaller hotspot radii. As the hotspot size decreased, the fraction of uncontaminated soil within the detector field of view increased, thus reducing the weighted average concentration reading. For reference, typical NaI and HPGe MDC values and the 3*FRL uranium hotspot criterion are also shown on the graph. This figure illustrates that a uranium hotspot with a concentration of 250 mg/kg will not be flagged as a hotspot unless the hotspot occupies most of the detector field of view, which is a 2.5-meter radius circle for a 31 cm high HPGe detector or a 2.3-meter radius circle for a 31 cm high NaI detector. The figure also demonstrates that a hotspot with a true total uranium concentration of 500 mg/kg will not be identified as a hotspot if its radius is less than approximately 0.8 meters. For a 1000 mg/kg hotspot, its radius must be at least 0.4 meters to be flagged as a hotspot by a 31 cm high detector.

Figure 3-10 also can be used to determine the radius at which a given level of uranium contamination becomes undetectable by a typical HPGe or NaI detector by locating the point where the detector measured output curve crosses the appropriate MDC trace. For example, a 250 mg/kg hotspot must have

a radius of at least 0.6 meters, to be detected as contamination by NaI instruments. When using a typical HPGe detector, contamination would be detectable until the 250 mg/kg hotspot radius decreased to less than 0.2 meters. This example reiterates the point made above that hotspots below a certain minimum size (i.e., hotspots with detector output readings below the MDC line on Figure 3-10) will not be detected at all. Additionally, there is a range of sizes, above this minimum, where the detector reading will indicate that contamination is present; but the results will have a low bias such that the contamination is not properly classified as a hotspot. On Figure 3-10, this would be the case for detector output readings between the 3*FRL line and the MDC line.

3.3.1.2 Hot Spot Confirmation

Phase II of the hotspot evaluation process involves both verifying the presence of hotspots and delineating their boundaries. Confirmation of potential hot spots identified by Phase I NaI measurements is prudent inasmuch as false positives may occur, particularly when count times as short as 4-seconds are used. Any Phase I location that exceeds three times the FRL for U-238, Th-232 and/or Ra-226 will be flagged for follow-up Phase II measurements with HPGe systems. Additionally, for Phase I NaI measurements, the location that yielded the highest total gamma activity will be also evaluated.

A hot spot is confirmed if the Phase IIa HPGe measurement exceeds three times the FRL for the relevant isotope. If the hot spot is confirmed, the extent of the hot spot will be delineated using Phase IIb HPGe measurements. Both Phase IIa and Phase IIb measurements are performed with HPGe systems at a height of 31 cm and a count time of 5 minutes.

3.3.1.3 Hot Spot Delineation

Hot spots identified by Phase I HPGe measurements or confirmed by Phase IIa HPGe measurements will be delineated using the Phase IIb measurement protocol in Table 3-3. This process calls for four additional measurements that surround the initial measurement (at a distance of 6 m for a 100 cm HPGe shot) in each of the principal compass directions. If all 4 measurements are below three times the FRL, the hot spot is delineated as the area of the initial measurement. For a Phase I HPGe measurement at a height of 100 cm, this would correspond to a hot spot area of about 100 m^2, and for a Phase IIa HPGe shot at 31 cm, the area of the hot spot would be approximately 20 m^2. If the result of any of the four measurements exceeds three times the FRL for any of the isotopes of interest, new measurement locations will be set up 4 m from the first Phase IIb measurement moving outward from the center of the hot spot. This process will be repeated, as needed, until the boundary of the hot spot has been reached (i.e., until concentrations are below three times the FRLs). The hot spot boundary will be established on

the basis of the set of measurement locations where the measurement results first drop below three times the FRL for all isotopes of interest. An example of the general hotspot delineation process is provided on Figure 3-11.

3.3.1.4 Hot Spot Maps

After the Phase IIb HPGe measurements define the extent of each hot spot, this information, in the form of maps, is provided to the construction manager and the characterization group so that all hotspots can be tracked and flagged for excavation. The initial hotspot maps will consist of results from NaI and HPGe measurements that identify and delineate the extent of all identified hotspots.

After the hot spots have been removed, Phase III verification measurements will be performed with HPGe systems to verify that remedial actions have reduced the U-238, Th-232 and/or Ra-226 activities in the hotspot footprints to values less than three times the FRL.. If the Phase III measurements indicate that U-238, Th-232 and/or Ra-226 levels in excess of three times the FRL still exist, then Phase IIb measurements are performed again to delineate the extent of the hot spot. When Phase III measurements show that U-238, Th-232 and Ra-226 activities are below three times the FRL, the area is considered to be ready for certification. A second set of maps will be produced after the Phase III measurements are complete to demonstrate that no hot spots remain in the area. The second set of maps will be provided to the characterization group for inclusion in the Certification Design Letter, which is submitted to USEPA and OEPA to initiate the certification process

3.3.2 Precertification PSP Overview

This section summarizes the use of real-time systems during precertification and discusses a number of considerations regarding the use of these systems that should be addressed in the preparation of related PSPs. Predesign real-time data may be used as precertification data if the predesign results showed the absence of above-WAC levels of uranium and no hot spots, provided the area has remained undisturbed since the predesign measurements were collected. Precertification measurements with NaI and HPGe systems will cover as close to 100 percent of the surface soil as possible. Activities during precertification that involve the use of real-time systems may include the following:

- Perform a real-time scan of the area to be certified prior to collecting certification samples
- Detect and delineate hot spots.

Specific real-time measurement activities may include the following:

- Perform NaI and HPGe measurements during Phase I, and HPGe measurements during Phase II and Phase III
- Prepare maps of NaI and HPGe results to identify hot spots and verify their removal.

Questions that should be considered in the preparation of PSPs may include the following:

- What organizations would be involved in executing the PSP?
- What real-time systems are most appropriate to survey the various areas?
- What documents, procedures, methods, and standards apply to various activities?
- What are applicable FRLs for the affected areas?
- What ASL level is required for measurements and data validation?
- What numbering system will be employed for measurements?
- What routine QA/QC procedures are required?
- What field QC measurements are needed?
- What maps are required?
- What mapping van functions are required?
- What safety and health provisions must be made to protect field crews?
- What are the requirements for data management.

3.3.3 Guidance

- Hot spot definitions only apply to U-238, Th-232 and Ra-226.
- The minimum detectable concentrations of the mobile NaI scanning systems are low enough that hotspots having contamination levels of 3*FRL (i.e. 246 mg/kg for total uranium, 4.5 pCi/g for Th-232 and 5.4 pCi/g for Ra-226) can be detected with a single 4-second measurement, assuming the hotspot is nearly equal in size to the detector field of view. However the NaI vehicles are not sensitive enough to detect hotspots in areas where the uranium FRL is 10 or 20 mg/kg.
- For Phase I investigations, the HPGe may be used to evaluate areas for the potential presence of hot spots if it is not practical to use NaI systems. In this case HPGe measurements will be taken at a height of 100 cm on a triangular grid (11-m node spacing) that provides 100 percent coverage for the area of concern.
- If any HPGe result is greater than three times the FRL, a hot spot has been identified and additional action must be taken.
- Areas where the actual contaminant concentrations exceeds 3*FRL may result in detector readings below 3*FRL if the area of the hotspot is very small (Figure 3-10 illustrates the relationship between hotspot size and its detectability). Very small hot spots may be recognizable visually, such as by noticing changes in soil color, and elevated activity may be detected via hand-held survey meters.
- If a localized contamination spot has an area equal to 65% of the field of view of the detector being used to characterize the surroundings, the measurement result will be biased low by 18%. This is true for both NaI and HPGe detectors, regardless of the detector height. Smaller hotspots will have larger biases.
- Both laboratory and time-of-day radon corrections must be applied to Ra-226 data before deciding if a hotspot action level has been exceeded.

3.3.4 See Also

2.0 *In Situ* Gamma Systems Operated at the FCP
4.5 Detector Field of View and Area Coverage
4.6 HPGe Grid Configurations
4.10 Use of Hand-Held Survey Meters
5.4 Minimum Detectable Concentrations
5.6 Radium-226 Corrections

3.4 CERTIFICATION INVESTIGATIONS

During the certification process, real-time instruments will be deployed to delineate hot spots that are identified by the results from physical samples (Figure 3-9). If a certification sample indicates that U-238, Th-232 or Ra-226 exceeds twice its FRL, HPGe systems will be used to delineate the extent of the hot spot, which is defined as two times the FRL during the certification process (Table3-4).

All certification sample locations where laboratory analyses exceed two times the FRL will be flagged for an HPGe measurement. Five-minute HPGe counts at 15 cm and 31 cm will be performed as the first step in the process to confirm and delineate these hot spots. If both the 15-cm and 31 cm measurements are below two times the FRL for all three isotopes, the presence of the hot spot is not confirmed, indicating that the laboratory result could have been erroneous or the hot spot could have been of very small extent. As a conservative measure, the area of the 15-cm measurement will be excavated to a depth of 6 inches and a verification measurement will be collected to demonstrate the absence of deeper contamination that could have affected the physical sample. If the 15-cm HPGe shot is above 2*FRL while the 31-cm shot is less than two times the FRL, then the hot spot will be considered to be area corresponding to the field of view of the 31-cm shot, since this represents the first areal measurement to drop below two times the FRL. In cases where both the 15-cm and the 31-cm HPGe shots yield results above two times the FRL for U-238, Th-232 or Ra-226, four additional 31-cm measurements, each 4 meters from the original 31-cm measurement location, will be performed (see Table 3-4). If the four additional measurements are all below two times the FRL, the hot spot boundary will be defined by the set of 4 measurement locations, since this represents the boundary where the measurement first fell below two times the FRL. However, if any of the four additional measurements gives a value greater than two times the FRL for any of the isotopes of concern, the measurement perimeter will be moved outward from the location(s) of the elevated reading(s) and additional 31-cm measurements will be performed. This process will continue until readings for all of the isotopes of concern fall below two times the FRL, and the hot spot boundary will be defined by the locations where all of the measurement results first fell below two times the FRL.

After the hot spot is delineated and removed, verification measurements are made to ensure that the levels of U-238, Th-232 and Ra-226 are less than twice their FRL. If these measurements indicate residual contamination exceeds two times the FRL for any of the three isotopes of interest, additional Phase I (hot spot delineation) measurements are performed to bound the extent of the hot spot. Real-time measurements will iterate between Phase I (delineation) and Phase II (verification of removal) until the hot spot has been removed and the footprint verified as less than two times the FRL. When making decisions regarding Ra-226 hotspots, the radium results must be radon corrected before comparing them with the hotspot limits.

3.4.1 Guidance

- HPGe measurements will be used to delineate the extent of hot spots identified by soil samples.
- HPGe measurements will be used to verify hot spot removal, i.e., that U-238, Th-232 and Ra-226 levels in the soil in the footprint of the hot spot are all less than two times their FRL.

3.4.2 See Also

2.0 *In Situ* Gamma Systems Used at the FCP
4.6 HPGe Grid Configurations
5.4 Minimum Detectable Concentrations
5.6 Radium-226 Corrections

3.5 PRE-SCAN OF SUSPECT HIGH CONTAMINAITON AREAS WITH HAND-HELD nanoSPEC

When scanning soil in potential high-contamination zones, like that expected in Area 6, the FCP waste pits, there is a concern that the wheels and other components of the various NaI scanning vehicles may become highly contaminated. This could spread radioactive contamination to other areas and could elevate instrument background, affecting the accuracy of measurement results. To prevent either of these situations, the mobile NaI systems are generally decontaminated on a daily basis to remove potential contamination prior to post-operational QC checks and proper storage. As noted in Section 2.6 of this manual, the nanoSPEC is a scanning tool that could operate without contacting contaminated surfaces in areas where high contamination is suspected. Because it is hand-held and can easily be covered with thin plastic wrap, there is little danger of this detector becoming contaminated during routine use. It was also noted in Section 2.6 that, because this detector is smaller than the other NaI detectors, it has higher detection limits. Consequently, its use is primarily limited to "pre-scans" of areas that are suspected of being highly contaminated, as this application allows the RTIMP personnel to avoid contaminating the 4"x4"x16" NaI systems. Theoretically, a pre-scan with a nanoSPEC could be deemed necessary during any of the four phases of remediation. However, it is most likely that a pre-scan would be necessary during predesign or soil excavation and segregation, and very unlikely that it would be needed during

precertification or certification. Regardless of which remediation phase it may occur in, the pre-scan will always be conducted in the same way.

3.5.1 Mode of Operation

The purpose of the pre-scan with the 4"x4" nanoSPEC NaI detector is to identify highly contaminated material so that it can be removed before conducting a normal scan with one of the 4"x4"x16" NaI detectors. This will prevent the normal NaI tools from becoming highly contaminated. The use of the nanoSPEC will be limited to this special situation, where the risk of contaminating one of the other NaI tools is high, and decontamination is likely to be difficult.

Table 3-5 summarizes the deployment protocols for the nanoSPEC. The detector is hand-carried by an analyst at a height of 31-cm above the ground as he walks over the area in question at a speed of one mile per hour (1.5 feet/sec). Typically, back and forth, straight-line traverses of the area are made covering as near to 100% of the area as possible. The spacing between adjacent traverses will be ten feet. This spacing results in over six feet of overlap in the detector fields of view on adjacent passes, making it unlikely that high contamination spots of significant size will be missed. The objective of the pre-scan is to identify locations where elevated levels of uranium, Ra-226 and/or Th-232 are present. The most highly contaminated soil areas identified during the pre-scan will be removed and dispositioned appropriately. A uranium WAC trigger level of 728 mg/kg was established as part of the process of calibrating the nanoSPEC detector. Any nanoSPEC result above this value will be confirmed with an HPGe measurement, as an HPGe stand can be decontaminated quite easily, if need be. If the HPGe measurements confirm that the material is indeed above WAC, the material will be excavated and segregated accordingly. Characterization and WAO personnel will determine follow-up actions when elevated levels of Ra-226 and/or Th-232 are encountered, bearing in mind that a key objective is to avoid severe contamination of the 4"x4"x16" NaI systems that are used to perform the routine real-time scans.

At the time that this document was issued, GPS data are not automatically merged with the nanoSPEC spectral analysis results. However, the nanoSPEC data collection protocol in Table 3-5 outlines the procedure that will be used to associate a physical location with each 4-second gamma ray spectrum. If, in the future, the programming is completed to automatically merge GPS and spectral data, the manual interpolation procedure outlined in Table 3-5 will no longer be necessary.

3.5.2 Follow-up Measurements

The nanoSPEC detector is not intended to replace or serve as a substitute for any of the 4"x4"x16" mobile NaI systems. Rather, it is intended to prevent contamination of these systems. Consequently, even though

an area was completely scanned with a nanoSPEC, it must also be surveyed with one of the 4"x4"x16" systems, just as if the nanoSPEC pre-scan had not occurred. So, two kinds of follow-up measurements will generally occur after a nanoSPEC scan: 1) HPGe measurements to confirm potential WAC exceedances identified by the nanoSPEC, and 2) routine mobile NaI measurements after the highly contaminated hotspots have been removed. As outlined in Tables 3-1 through 3-4, additional HPGe confirmation and delineation measurements may be required as a follow-up to the routine NaI scan performed with one of the 4"x4"x16" systems.

TABLE 3-1
MEASUREMENT PROTOCOL FOR PREDESIGN INVESTIGATIONS

PHASE I – Initial Measurements – Identify contamination extent and potential above-WAC zones
NaI Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet; mobilize to the field. 3) Obtain and record moisture readings (Dynamax or Zeltex; see RTIMP-M-003). 4) Begin acquisition of 4-second measurements (i.e., one spectrum every 4 seconds). 5) Scan at nominal height of 31 cm and nominal speed of 1 mile/hr. 6) Area coverage is based on a 13-ft center-to-center separation between adjacent NaI passes (giving approximately 2 ft of overlap on adjacent passes). 7) Acquire a single batch file per instrument per area/lift per day (obtain average 'z' from Surveying). 8) Perform post-operational check(s) and record file number(s). 9) Complete the entry of information on the electronic worksheet. 10) Apply moisture and laboratory radon corrections to measurement results. 11) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5508). 12) Plot single spectrum dry weight total uranium (mg/kg) and (as needed) single spectrum Ra-226 (pCi/g), Th-232 (pCi/g) and total activity (cps) maps. 13) Identify general contamination patterns by reviewing uranium, thorium, radium and total activity maps. 14) Identify all areas that exceed the uranium WAC trigger level of 875 mg/kg. 15) Provide information to Characterization and WAO groups. 16) Perform Phase II HPGe measurements in areas where uranium exceeds 875 mg/kg.
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field, lay out triangular grid (11-m node spacing) and acquire GPS coordinates. 4) Obtain and record moisture readings at each node location (Dynamax or Zeltex; see RTIMP-M-003). 5) Set up HPGe detector at a height of 100 cm, count for 5 minutes, and save the spectrum. 6) Repeat set-up and measurements until area is covered. 7) Perform post-operational check(s) and record file number(s). 8) Complete the entry of information on the electronic worksheet. 9) Apply moisture and laboratory radon corrections to measurement results. 10) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 11) Plot dry weight total U (mg/kg) and (as needed) Ra-226 (pCi/g) and Th-232 (pCi/g) maps. 12) Identify general contamination patterns by reviewing map(s). 13) Identify all areas that exceed the uranium WAC trigger level of 400 mg/kg. 14) Provide information to Characterization and WAO groups. 15) Perform Phase II HPGe measurements in areas where uranium exceeds 400 mg/kg.

TABLE 3-1
(Continued)

PHASE II – Above WAC Confirmation & Delineation – Sampling guidance
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC.
2) Record initial information on the electronic worksheet
3) Mobilize to the field to confirm the Phase I AWAC measurements.
4) Use a frisker to identify the area of maximum activity for each Phase I AWAC measurement.
5) Acquire GPS coordinates for each area of maximum activity and flag each location.
6) Obtain and record moisture readings at each location (Dynamax or Zeltex; see RTIMP-M-003).
7) Set up HPGe detector at a height of 31 cm, count for 5 minutes, and save the spectrum.
8) Repeat set-up and measurement at each location.
9) Perform post-operational check(s) and record file number(s).
10) Complete the entry of information on the electronic worksheet.
11) Apply moisture and laboratory radon corrections to measurement results.
12) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509).
13) Plot dry weight total uranium values (mg/kg) on a map.
14) Identify all areas that exceed the uranium WAC trigger level of 928 mg/kg.
15) If no uranium AWAC soil is identified, provide map and QC form to Characterization and WAO groups.
16) If uranium AWAC soil is present, perform additional measurements to delineate extent (Step 17).
17) Lay out grid with flags (4-m node spacing) around the AWAC zone.
18) Acquire the GPS coordinates for each node.
19) Repeat Steps 5 through 17 until the AWAC area has been bounded.
20) Provide information to Characterization and WAO groups.

NOTE: The LabVIEW HPGe software automatically performs moisture and laboratory radon corrections (Step 11) and logs the results after each spectral acquisition is complete. A review of this data file may be performed in the field before a map is produced. This will enable the analyst to perform Steps 16 through 19 before producing a map (Step 13) and before post-operational Steps 9 through 14 are performed.

TABLE 3-2
MEASUREMENT PROTOCOL FOR EXCAVATION MONITORING

PHASE I – Initial Measurements – Identify potential above WAC zones
NaI Systems[a]
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet; mobilize to the field. 3) Obtain and record moisture readings (Dynamax or Zeltex; see RTIMP-M-003). 4) Begin acquisition of 4-second measurements (i.e., one spectrum every 4 seconds). 5) Scan at nominal height of 31 cm and nominal speed of 1 mile/hr. 6) Area coverage is based on a 13-ft center-to-center separation between adjacent NaI passes (giving approximately 2 ft of overlap on adjacent passes). 7) Acquire a single batch file per instrument per area/lift per day (obtain average 'z' from Surveying). 8) Perform post-operational check(s) and record file number(s). 9) Complete the entry of information on the electronic worksheet. 10) Apply moisture and laboratory radon corrections to measurement results. 11) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5508). 12) Plot single spectrum dry weight total uranium (mg/kg) and (as needed) single spectrum Ra-226 (pCi/g), Th-232 (pCi/g) and total activity (cps) maps. 13) Identify all areas that exceed the uranium WAC trigger level of 875 mg/kg. 14) Provide information to Characterization and WAO groups. 15) Perform Phase II HPGe measurements in areas where uranium exceeds 875 mg/kg.
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field, lay out triangular grid (11-m node spacing) and acquire GPS coordinates. 4) Obtain and record moisture readings at each node location (Dynamax or Zeltex; see RTIMP-M-003). 5) Set up HPGe detector at a height of 100 cm, count for 5 minutes, and save the spectrum. 6) Repeat set-up and measurements until area is covered. 7) Perform post-operational check(s) and record file number(s). 8) Complete the entry of information on the electronic worksheet. 9) Apply moisture and laboratory radon corrections to measurement results. 10) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 11) Plot dry weight total U (mg/kg) and (as needed) Ra-226 (pCi/g) and Th-232 (pCi/g) maps. 12) Identify all areas that exceed the uranium WAC trigger level of 400 mg/kg. 13) Provide information to Characterization and WAO groups. 14) Perform Phase II HPGe measurements in areas where uranium exceeds 400 mg/kg.
PHASE II – Above WAC Confirmation & Delineation – Excavation guidance and path for soil disposition
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet 3) Mobilize to the field to confirm the Phase I AWAC measurements. 4) Use a frisker to identify the area of maximum activity for each Phase I AWAC measurement. 5) Acquire GPS coordinates for each area of maximum activity and flag each location. 6) Obtain and record moisture readings at each location (Dynamax or Zeltex; see RTIMP-M-003). 7) Set up HPGe detector at a height of 31 cm, count for 5 minutes, and save the spectrum. 8) Repeat set-up and measurement at each location. 9) Perform post-operational check(s) and record file number(s). 10) Complete the entry of information on the electronic worksheet. 11) Apply moisture and laboratory radon corrections to measurement results. 12) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 13) Plot dry weight total uranium values (mg/kg) on a map. 14) Identify all areas that exceed the uranium WAC trigger level of 928 mg/kg. 15) If no uranium AWAC is identified, provide map and QC form to Characterization and WAO groups. 16) If uranium AWAC soil is present, perform additional measurements to delineate extent (Step 17). 17) Lay out grid with flags (4-m node spacing) around the AWAC zone.

TABLE 3-2
(Continued)

PHASE II – Above WAC confirmation & delineation – Excavation guidance and path for soil disposition
HPGe Systems[c] (continued)
18) Acquire the GPS coordinates for each node. 19) Repeat Steps 5 through 17 until the AWAC area has been bounded. 20) Provide information to Characterization and WAO groups.
PHASE III – Verification of the removal of above-WAC soil
NaI Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field and locate area that has been excavated to remove AWAC soil. 4) Obtain and record moisture readings (Dynamax or Zeltex; see RTIMP-M-003). 5) Begin acquisition of 4-second measurements (i.e., one spectrum every 4 seconds). 6) Scan at nominal height of 31 cm and nominal speed of 1 mile/hr. 7) Area coverage is based on a 13-ft center-to-center separation between adjacent NaI passes (giving approximately 2 ft of overlap on adjacent passes). 8) Acquire a single batch file per instrument per area per day (obtain average 'z' from Surveying). 9) Perform post-operational check(s) and record file number(s). 10) Complete entry of information on the electronic worksheet. 11) Apply moisture and laboratory radon corrections to measurement results. 12) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5508). 13) Plot single spectrum dry weight total uranium values (ppm) on a map. 14) If areas still exceed the uranium WAC trigger level of 875 mg/kg total U, repeat Phase II. 15) Provide information to Characterization and WAO groups.
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field and locate area that has been excavated to remove AWAC soil. 4) Lay out rectangular grid (11-meter or 4-meter node spacing depending on whether the HPGe detector height will be 100 cm or 31 cm) and acquire GPS coordinates of all grid nodes. 5) Obtain and record moisture readings at each node location (Dynamax or Zeltex; see RTIMP-M-003). 6) Set up HPGe detector, count for 5 minutes and save the spectrum. If an 11-m grid was laid out, set the detector at a height of 100 cm. If a 4-m grid was established, set the detector at a height of 31 cm. 7) Repeat set-up and measurements until area is covered. 8) Perform post-operational check(s) and record file number(s). 9) Complete the entry of information on the electronic worksheet. 10) Apply moisture and laboratory radon corrections to measurement results. 11) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 12) Plot dry weight total uranium values (mg/kg) on a map. 13) If areas still exceed the uranium AWAC trigger level (400 mg/kg for 100-cm detector height or 928 mg/kg for 31-cm detector height), repeat Phase II measurements. 14) Provide information to Characterization and WAO groups.

TABLE 3-3
MEASUREMENT PROTOCOL FOR PRECERTIFICATION ACTIVITIES

PHASE I – Initial Measurements (radon monitoring is not required)
NaI Systems
1) Verify NaI instrument has MDCs less than 3*FRL for total U, Th-232 and Ra-226. 2) Perform pre-operational check and record file number – daily QC. 3) Record initial information on the electronic worksheet. 4) Mobilize to the field. Obtain and record moisture readings (Dynamax or Zeltex; see RTIMP-M-003). 5) Begin acquisition of 4-second measurements. 6) Scan at nominal height of 31 cm and nominal speed of 1 mph. 7) Area coverage is based on a 13-ft center-to-center separation between adjacent NaI passes (giving approximately 2 ft of overlap on adjacent passes). 8) Acquire a single batch file per area per day (obtain average 'z' from Surveying). 9) Perform post-operational check(s) and record file number(s). 10) Complete the entry of information on the electronic worksheet. 11) Apply moisture and laboratory radon corrections to measurement results. 12) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5508). 13) Examine the single spectrum results for total U, Th-232 and Ra-226. Identify all areas that exceed the hot spot criterion of 3*FRL for each isotope. 14) If no hotspots are found, identify the location of the highest total counts/sec for each batch. 15) Perform Phase IIa measurements on all identified hotspots and on the highest total counts/sec measurement.
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field, lay out grid (11-m node spacing) and acquire GPS coordinates for each node. 4) Obtain and record moisture readings at each node location (Dynamax or Zeltex; see RTIMP-M-003). 5) Set up HPGe detector at a height of 100 cm, count for 5 minutes, and save the spectrum. 6) Repeat set-up and measurements until area is covered. 7) Perform post-operational check(s) and record file number(s). 8) Complete the entry of information on the electronic worksheet. 9) Apply moisture and laboratory radon corrections to measurement results. 10) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 11) Identify all areas that exceed hot spot criteria of 3*FRL for total U, Th-232, and Ra-226 and record locations. 12) If no hotspots are found, precertification scanning in the area covered by HPGe is complete. 13) Provide information to Characterization and WAO groups. 14) Perform Phase IIb measurements on all hotspots identified[a].
PHASE IIa[a] – Hotspot Confirmation for Phase I NaI Measurements Only (radon monitor is required for radium hotspots)
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field; acquire GPS coordinates (based on Phase I results). 4) Use a frisker to identify the area of maximum activity for each Phase I hot spot measurement, if possible. 5) Acquire GPS coordinates for each area of maximum activity and flag each location. 6) Obtain and record moisture readings at each location of maximum activity (Dynamax or Zeltex; see RTIMP-M-003). 7) Set up HPGe detector at a height of 31 cm, count for 5 minutes, and save the spectrum. 8) Review the spectrum to determine if total U, Ra-226 and/or Th-232 exceeds 3*FRL (i.e., a hotspot). If Ra-226 hotspot is suspected, radon correct Ra-226 results before testing against hotspot criterion[b]. 9) If a hotspot is not present, go to Step 11. 10) If a hotspot is present, proceed to Phase IIb measurements[a]. 11) Repeat set-up and measurements at other locations. 12) Perform post-operational check(s) and record file number(s). 13) Complete the entry of information on the electronic worksheet. 14) Apply moisture (and radon corrections if appropriate) to measurement results. 15) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 16) Provide information to Characterization and WAO groups.

TABLE 3-3
(Continued)

PHASE IIb – Delineation of Hotspots (radon monitor is required for radium hotspots)[a]
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet; mobilize to the field. 3) For Phase I HPGe hotspots, step out 6 m from the center in the N, S, E & W direction. 4) For Phase IIa HPGe hotspots, step out 4 m from the center in the N, S, E & W direction. 5) Flag each location and acquire GPS coordinates and moisture measurements. 6) Set up HPGe detector at a height of 31 cm, count for 5 minutes, and save the spectrum. 7) Review the spectrum to determine if total U, Ra-226 and/or Th-232 exceeds 3*FRL (i.e., a hotspot). If Ra-226 hotspot is suspected, radon correct Ra-226 results before testing against hotspot criterion.[b] 8) If any of the four 31-cm shots exceed 3*FRL, continue delineation as described below. 9) If the four initial Phase IIb HPGe shots at 31 cm are less than 3*FRL, mark hotspot boundary as: a. area of 100 cm Phase I HPGe shot; go to Step 15 b. area of 31 cm Phase IIa shot; go to Step 15. 10) Step out 4 m in the N, S, E and W (but not back toward the original hotspot) from the location of any 31-cm HPGe shot that exceeded hotspot criteria. 11) Flag each location and acquire GPS coordinates and moisture measurements. 12) Repeat Steps 6, 7 and 8 for each additional 31-cm HPGe shot. 13) If the additional 31-cm HPGe shots are less than 3*FRL, designate hotspot boundary as the outer perimeter of the fields of view of the measurements with results above 3*FRL; go to Step 15. 14) If any of the additional 31-cm shots exceed 3*FRL, repeat Steps 10 - 13 until hotspot is delineated. 15) Repeat set-up and measurements at other locations. 16) Perform post-operational check(s) and record file number(s). 17) Complete the entry of information on the electronic worksheet. 18) Apply moisture (and radon corrections if appropriate) to measurement results. 19) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 20) Generate precertification maps and provide information to Characterization and WAO groups.
PHASE III – Verification of the Removal of Hotspot(s) (radon monitor is required for radium hotspots)
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC. 2) Record initial information on the electronic worksheet. 3) Mobilize to the field and locate area that has been excavated to remove hotspot(s). 4) Lay out a grid with flags (4-m node spacing) and acquire GPS coordinates of each flag. Ensure that 100% coverage of the excavation footprint is obtained. 5) Obtain and record moisture readings at each node (Dynamax or Zeltex; see RTIMP-M-003). 6) Set up HPGe detector at a height of 31 cm, count for 5 minutes, and save the spectrum. 7) Repeat set-up and measurements until area is covered. 8) Perform post-operational check(s) and record file number(s). 9) Complete the entry of information on the electronic worksheet. 10) Apply moisture and radon corrections if appropriate) to measurement results. 11) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509). 12) Plot the total uranium, Th-232 and/or Ra-226 values on a map. 13) If areas still exceed the hotspot criteria, repeat Phase II measurements. 14) Provide information to Characterization and WAO groups.

a. PHASE IIb measurements may be performed in parallel with PHASE IIa measurements.
b. Step 7 may be performed simultaneously with ongoing field measurements if the wireless Ethernet is supporting field operations.

TABLE 3-4
MEASUREMENT PROTOCOL FOR CERTIFICATION ACTIVITIES

PHASE I – Delineation of Hotspot(s) Identified by Physical Samples (radon monitor required for radium hotspots)
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC.
2) Record initial information on the electronic worksheet.
3) Mobilize to the field; find location(s) where sample(s) with elevated activity was collected using GPS coordinates or other means.
4) Use a frisker to identify the area of maximum activity in vicinity of sample location.
5) Acquire GPS coordinates for each area of maximum activity and flag each location.
6) Obtain and record moisture readings at each maximum activity location (Dynamax or Zeltex; see RTIMP-M-003).
7) Set up HPGe detector, acquire and save two five-minute spectra: one at 15 cm and one at 31 cm.
8) Review the spectra to determine if total U, Th-232 and/or Ra-226 exceed 3*FRL (i.e., a hotspot). If Ra-226 hotspot is suspected, radon correct Ra-226 results before testing against hotspot criterion[a].
9) Based on the two measurement results, proceed with one of the options listed below:
a. If both HPGe shots < 2*FRL: anomalous lab result or very localized contamination; NO HOT SPOT. Go to step 20.
b. If both HPGe shots > 3*FRL: delineate hotspot boundary with 31-cm HPGe shots as described in Steps 10 – 20.
c. If 15-cm shot is between 2*FRL and 3*FRL and 31 cm shot < 2*FRL: mark hotspot boundary as the field of view of the 31-cm HPGe shot. Go to Step 20.
d. If the 15-cm and 31 cm shots are both between 2*FRL and 3*FRL: delineate hotspot boundary with 31-cm HPGe shots as described in steps 10 – 20.
10) BEGIN DELINEATION by stepping out 4 m from the center of the first HPGe measurement in the N, S, E & W direction.
11) Flag each location and acquire the GPS coordinates.
12) Obtain and record moisture and 31-cm HPGe measurements at the four locations noted in Step 11.
13) Review the spectra to determine if total U, Th-232 and/or Ra-226 exceed 2*FRL. If Ra-226 hotspot is suspected, radon correct Ra-226 results before testing against hotspot criterion[a].
14) If the four 31-cm HPGe shots are <2*FRL, mark the hotspot boundary as the outer perimeter of the field of view of the original 31 cm shot collected in step 7; go to Step 20.
15) If any of the delineation HPGe shots in Step 12 exceeds 2*FRL, continue delineation by moving away from these shot locations, stepping out 4 m in the N, S, E, W directions (but not back toward the initial hotspot) from the center of each HPGe shot that exceeded 2*FRL
16) Flag each location and acquire the GPS coordinates.
17) Repeat moisture and HPGe measurements for each additional location.
18) If additional 31-cm HPGe shots are less than 2*FRL, designate hotspot boundary as the set of locations where HPGe results first fell below 2*FRL. Go to Step 20.
19) If any additional 31-cm shots exceed 2*FRL, repeat Steps 15 - 18 until hotspot is delineated.
20) Repeat set-up and measurements at other locations (Steps 4 through 19).
21) Perform post-operational check(s) and record file number(s).
22) Complete the entry of information on the electronic worksheet.
23) Apply moisture (and radon corrections if appropriate) to measurement results.
24) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509).
25) Provide information to Characterization and WAO groups.

TABLE 3-4
(Continued)

PHASE II – Verification of Hotspot Removal (radon monitor required for radium hotspot)
HPGe Systems
1) Perform pre-operational check(s) and record file number(s) – daily QC.
2) Record initial information on the electronic worksheet.
3) Mobilize to the field and locate area that has been excavated to remove hotspot(s).
4) Lay out a grid (4-m node spacing) and acquire GPS coordinates.
5) Obtain and record moisture readings at each node location (Dynamax or Zeltex; see RTIMP-M-003).
6) Set up HPGe detector at a height of 31 cm, count for 5 minutes, and save the spectrum.
7) Repeat set-up and measurements until area is covered.
8) Perform post-operational check(s) and record file number(s).
9) Complete the entry of information on the electronic worksheet.
10) Apply moisture (and radon corrections if appropriate) to measurement results.
11) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5509).
12) Plot the total uranium, Th-232 and/or Ra-226 values on a map.
13) If areas still exceed the hotspot criteria of greater than 2*FRL, repeat Phase I measurements.
14) Provide information to Characterization and WAO groups.

a. Steps 8 and 13 may be performed simultaneously with ongoing field measurements if the wireless ethernet is supporting field operations.

TABLE 3-5
PRE-SCAN OF SUSPECT HIGH CONTAMINATION AREA WITH NANOSPEC

NanoSPEC Pre-Scan – Identify Highly Contaminated Zones Prior to Normal NaI Scan
1) Perform pre-operational check(s) and record file number(s) – daily QC.
2) Record initial information on the electronic worksheet; mobilize to the field.
3) Comply with all RWP requirements, especially PPE requirements for entry into a contaminated area.
4) Use existing landmarks or place flags/stakes to mark off straight rows 10 feet apart as guides for traversing the area in question. Obtain GPS coordinates for each marker.
5) Obtain and record moisture readings (Zeltex preferred because surface contact is not necessary to obtain moisture measurement; see RTIMP M-003).
6) Begin acquisition of 4-second measurements (i.e., one spectrum every 4 seconds).
7) Scan at nominal height of 31 cm and nominal speed of 1 mile/hr (1.5 feet/sec.). Travel in a straight line between location markers and record the time and marker number as each marker is passed.
8) The distance between adjacent traverses of the area will be 10 feet.
9) Acquire a single batch file per instrument per run (obtain average 'z' from Surveying).
10) If requested to do so during the scan, mark all measurement locations having total U results above the WAC trigger for uranium (728 mg/kg) with paint or other suitable medium.
11) Perform post-operational check(s) and record file number(s).
12) Complete the entry of information on the electronic worksheet.
13) Verify the integrity of the collected spectra and complete data verification checklist (FS-F-5508).
14) Using the time/location data from step 7, determine the spectrum file that should be associated with each marker location. Then use the scan speed and interpolated times to assign a location to each of the intermediate spectral files.
15) Plot single spectrum dry weight total uranium (mg/kg) and (as needed) single spectrum Ra-226 (pCi/g), Th-232 (pCi/g) and total activity (cps) maps.
16) Identify general contamination patterns by reviewing uranium, thorium, radium and total activity maps.
17) Identify all areas that exceed the nanoSPEC uranium WAC trigger level of 728 mg/kg.
18) Provide information to Characterization or Construction and WAO groups.

a. Steps 10 through 13 may be performed in parallel with Steps 4 through 7 if the wireless ethernet is supporting field operations.

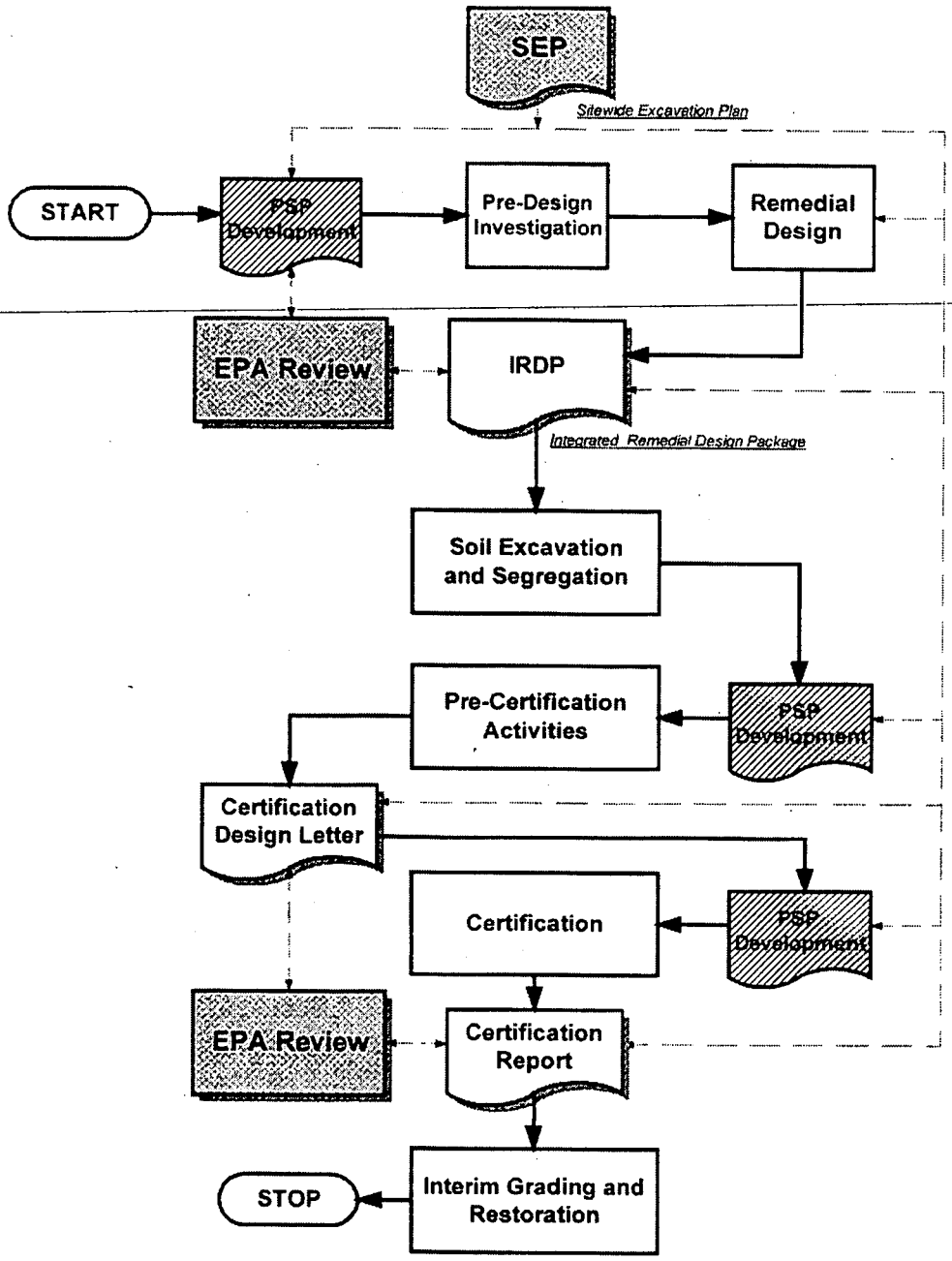


Figure 3-1. General Area-Specific Soil Remediation Process

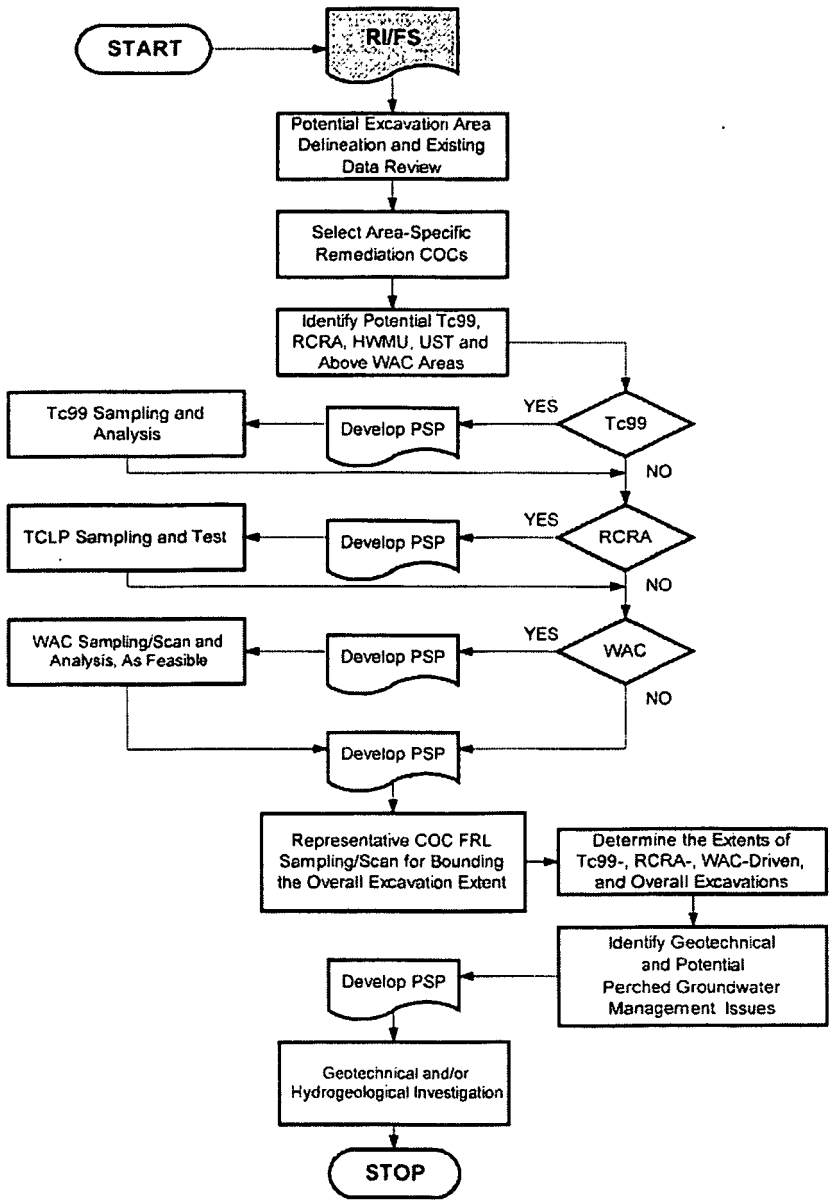


Figure 3-2. General Predesign Investigation Process

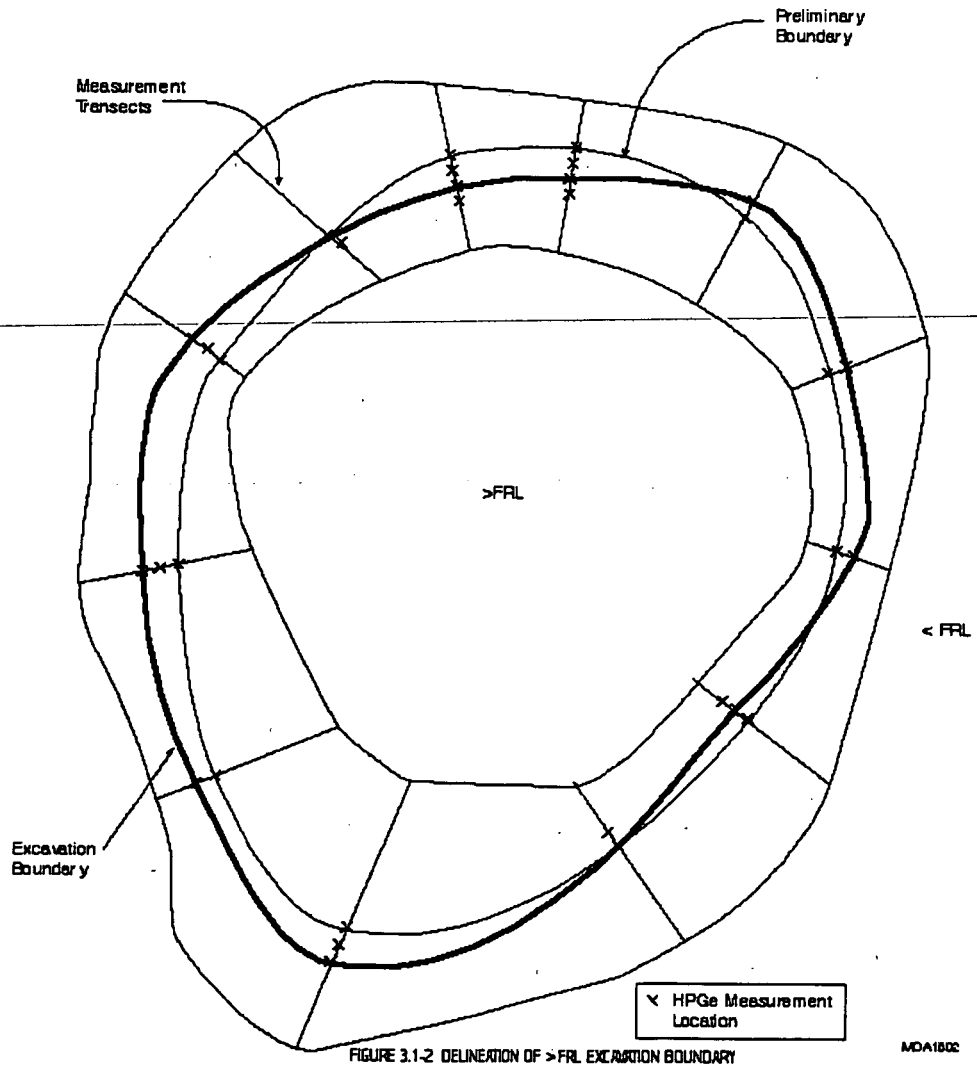


FIGURE 3.1-2 DELINEATION OF >FRL EXCAVATION BOUNDARY

Figure 3-3. Delineation of Above-FRL Excavation Boundary

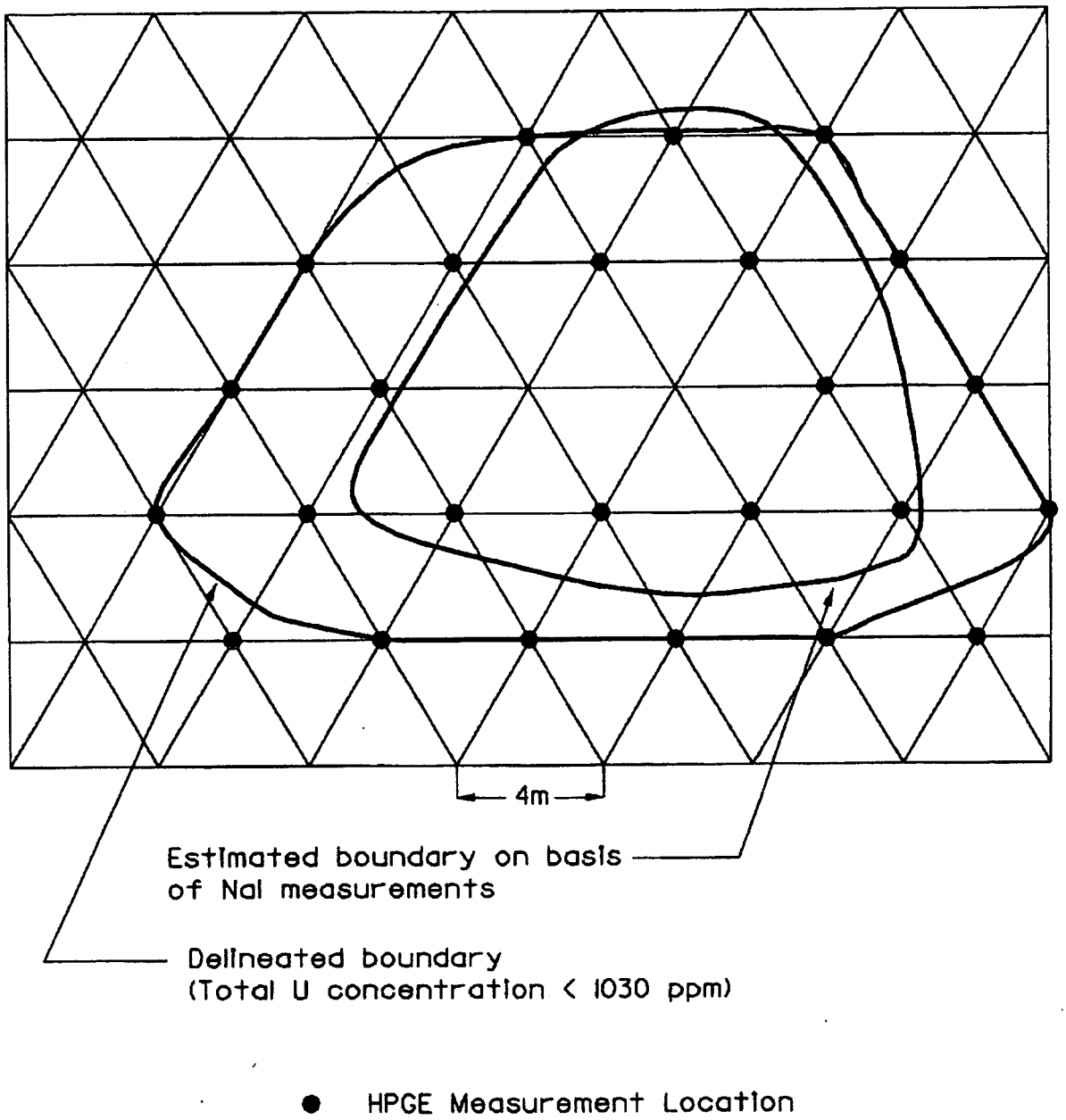


Figure 3-4. Example of Delineation of Above-WAC Soil

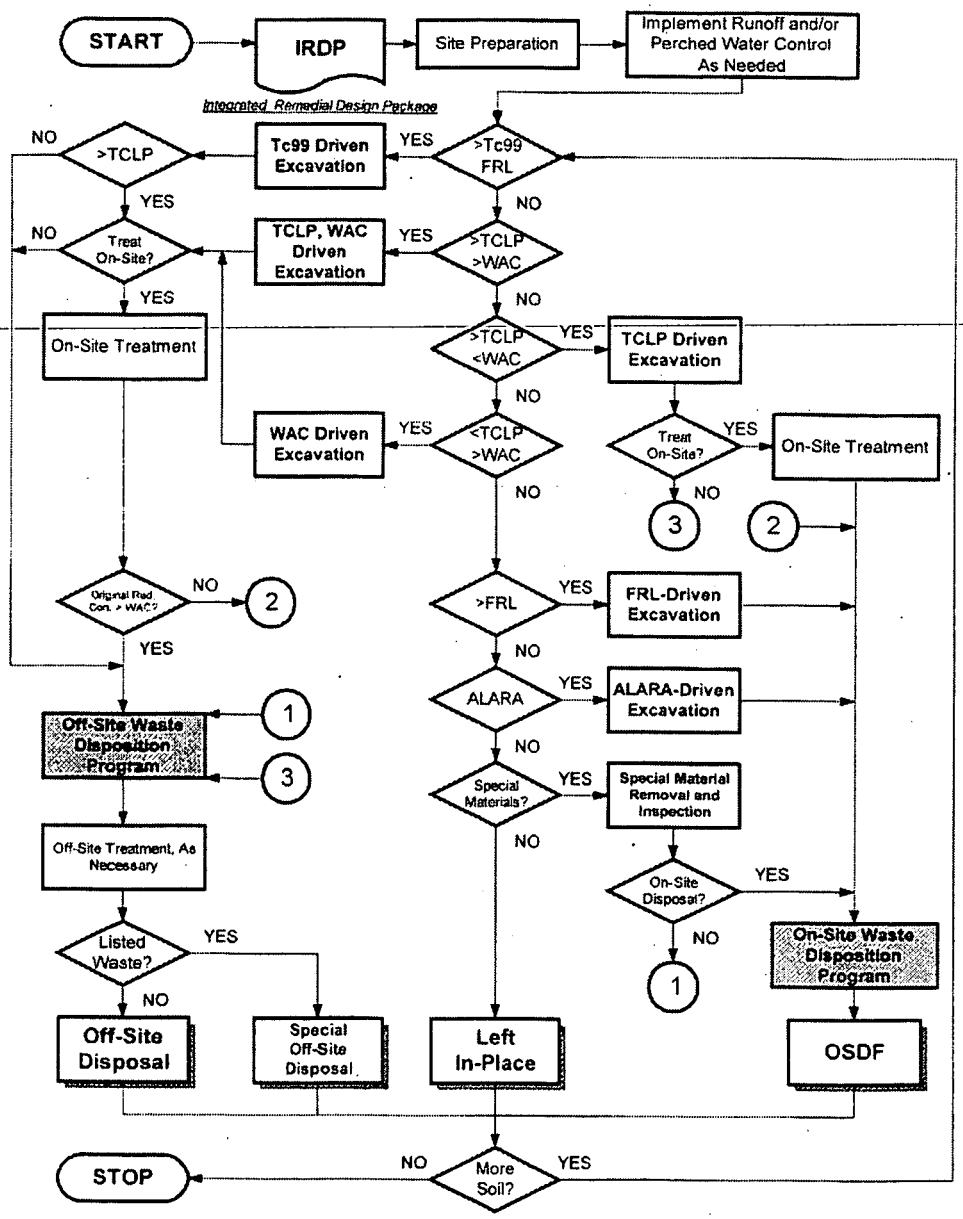


Figure 3-5. General Soil Segregation/Disposal Process

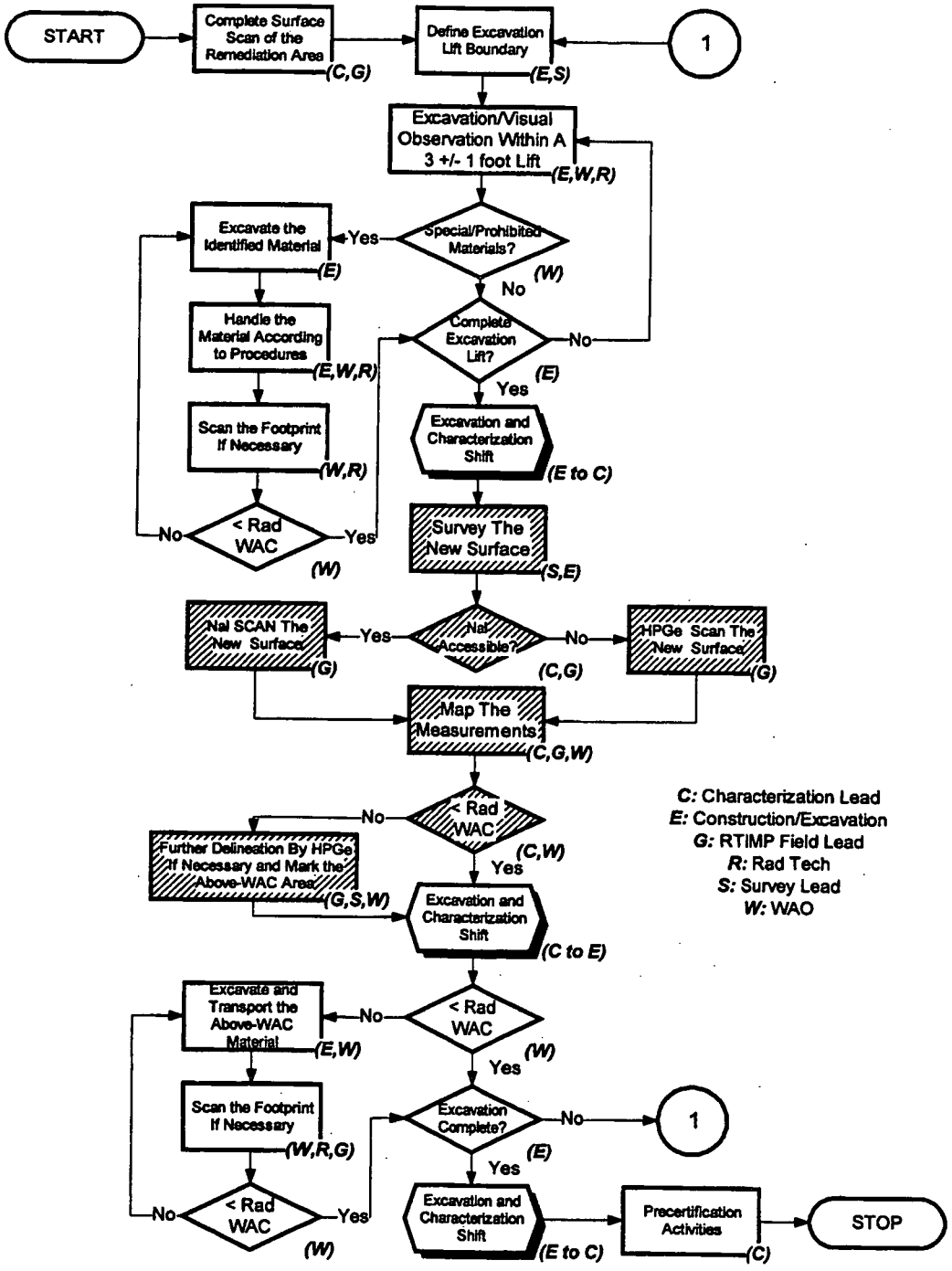


Figure 3-6. Excavation and Characterization Control Process

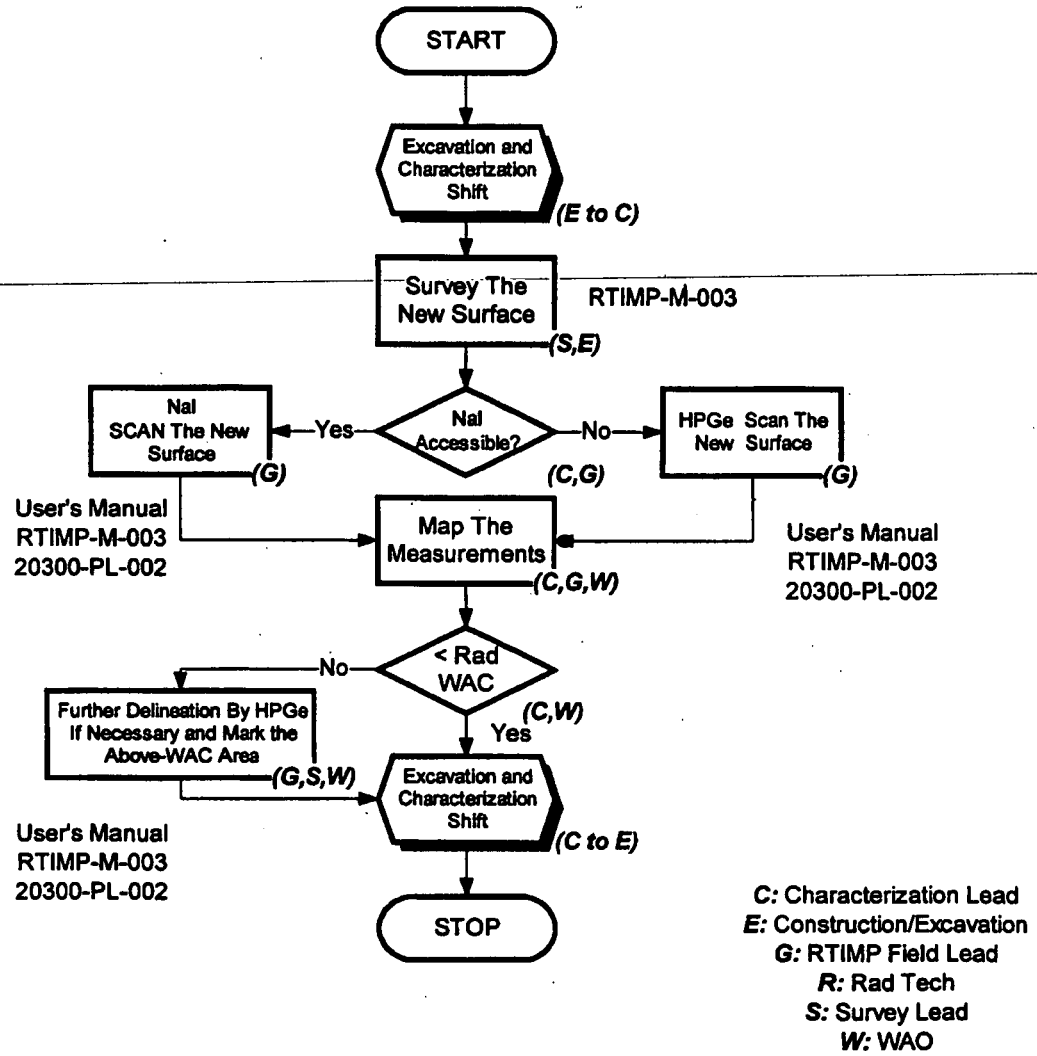


Figure 3-7. Applicable Operating Procedures and Guiding Documents

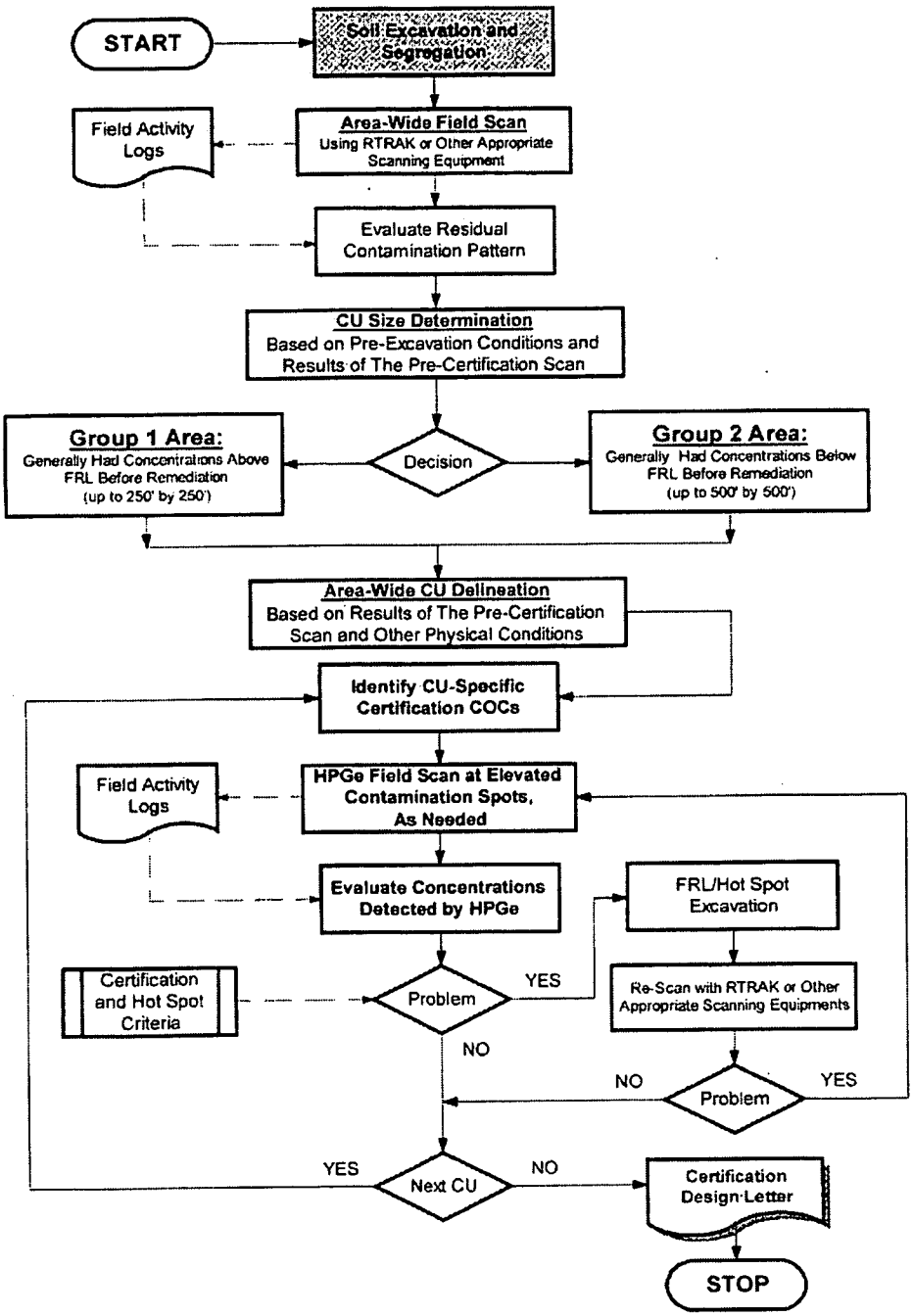


Figure 3-8. General Precertification Activities

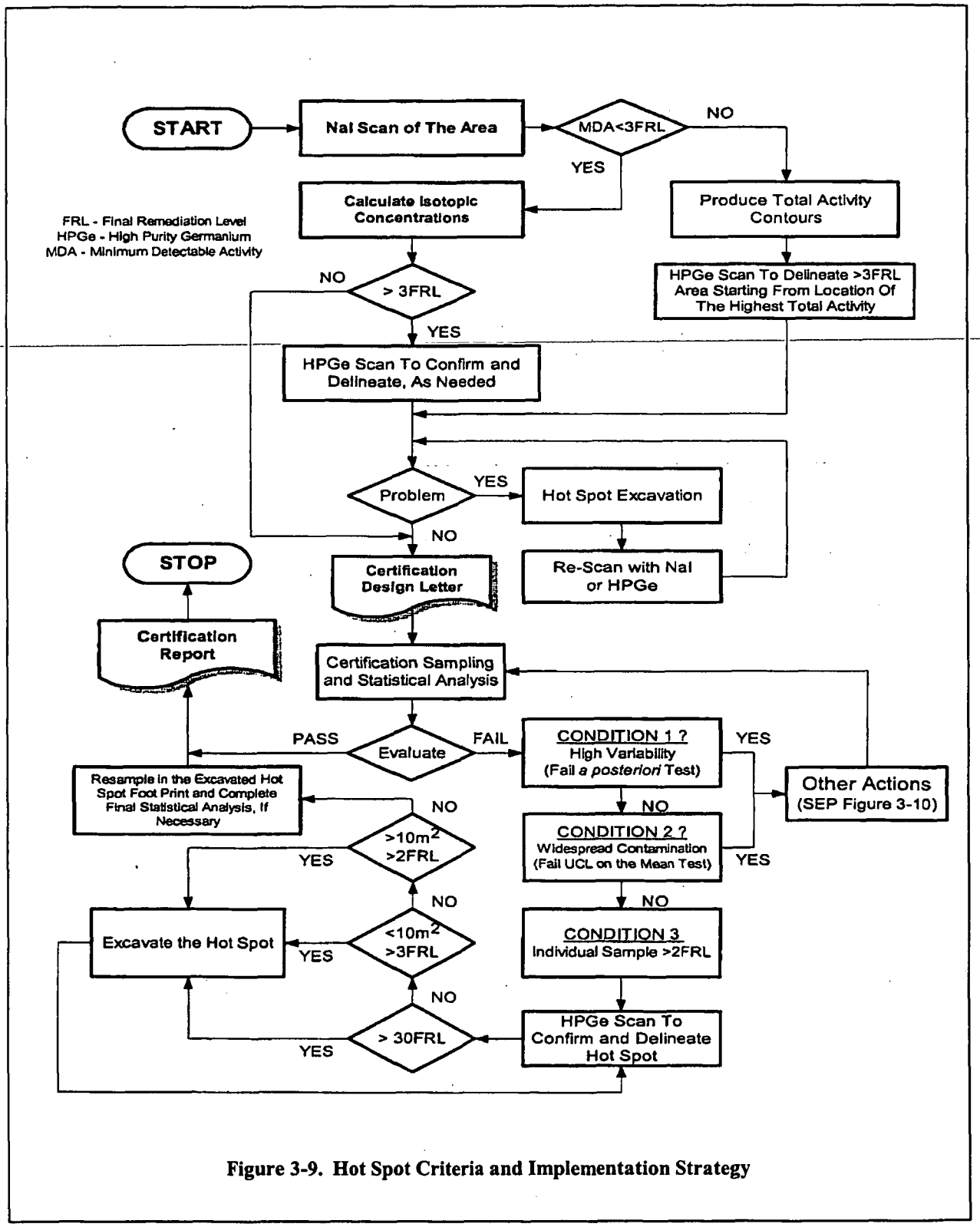


Figure 3-9. Hot Spot Criteria and Implementation Strategy

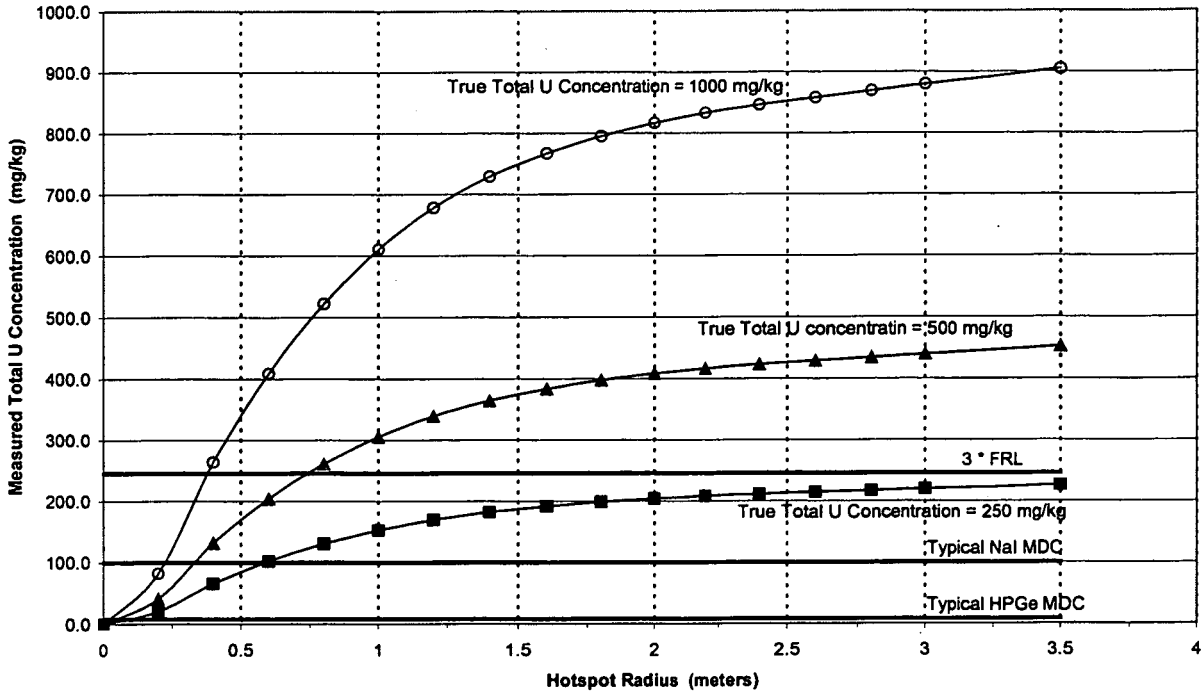


Figure 3-10. Measured Versus True Hotspot Activity as a Function of Hotspot Radius

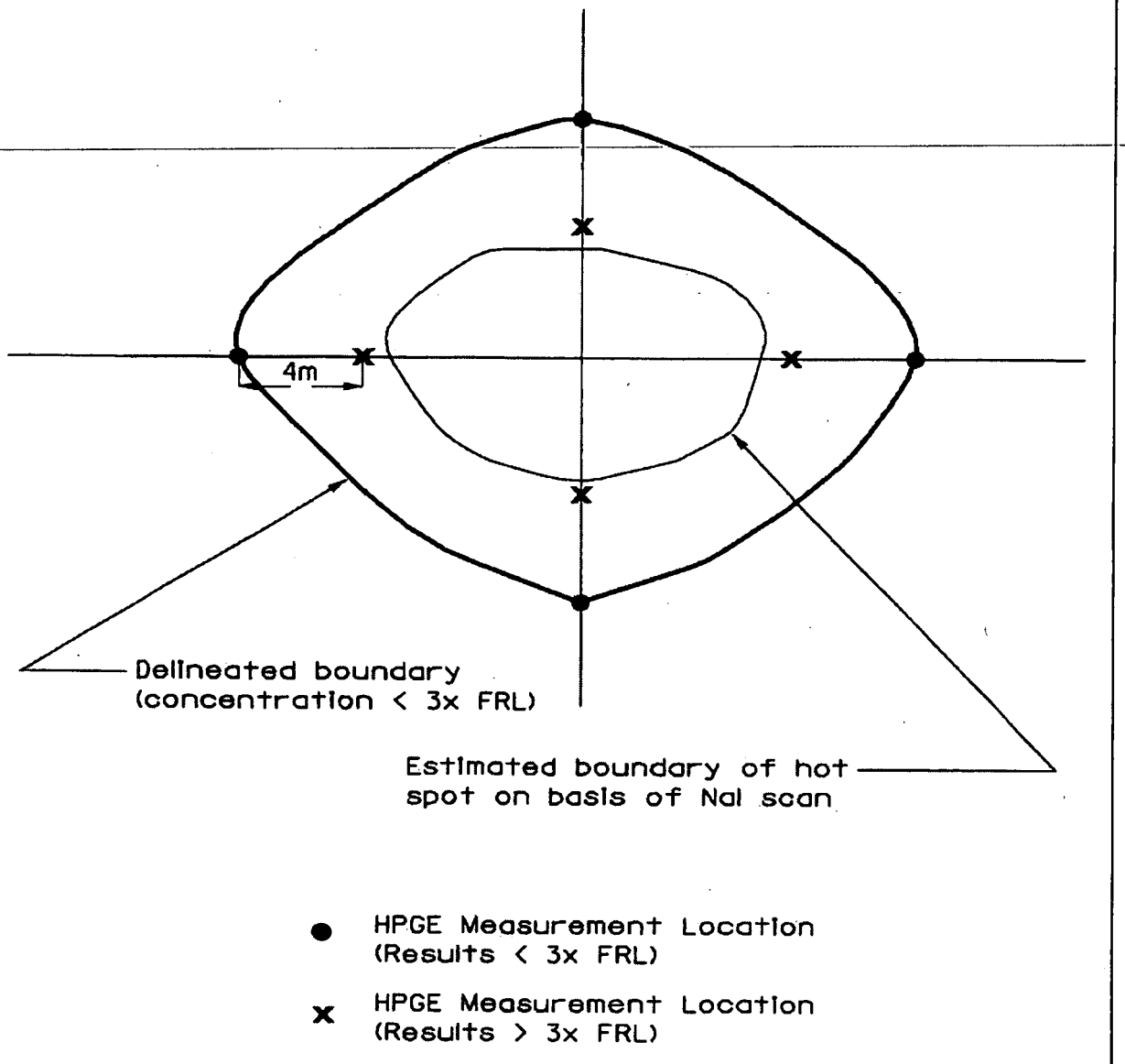


Figure 3-11. Example of Hot Spot Delineation

4.0 OPERATIONAL GUIDELINES AND DATA INTERPRETATION

This section contains practical information needed by project personnel who 1) plan *in situ* gamma spectrometry measurements, 2) interpret *in situ* gamma spectrometry data, 3) integrate *in situ* gamma spectrometry data with other data sets or into engineering designs, and 4) make decisions based upon *in situ* gamma spectrometry data. In particular, characterization personnel should be familiar with this section.

The information in this section is derived from multiple sources: the various comparability studies referenced in Section 1.0, the scientific literature (including DOE in-house publications), and previously unpublished calculations/interpretations based upon FCP *in situ* gamma spectrometry data. Where information is derived from FCP comparability studies or from the scientific literature, the reader is directed to the appropriate publication for supporting documentation, justification, and background. Where data, interpretations, or facts are unpublished, sufficient supporting documentation to justify assertions is included in the topic text.

4.1 DATA QUALITY LEVELS

Both the HPGe and NaI systems perform *in situ* measurements of gamma photons emitted from radionuclides in surface soil. However, certain situations and conditions exist which are more favorable for using one system over the other, and general protocols (Section 3.0) establish which system is used for a particular phase of the characterization activity (e.g., above-WAC scans). Although the RTIMP group is familiar with the application of the systems to field measurements, project personnel requesting real-time measurements should know and understand the measurement objectives, with respect to data quality objectives (DQO) and data quality levels, prior to initiating field work.

Tables 2-1 and 2-2 provide a basic overview of the possible uses of HPGe and NaI systems, and they also specify the data quality levels (ASLs) and measurement objectives of these systems. Unlike HPGe measurements which may be performed at either ASL A or ASL B. NaI measurements can only be performed at ASL A. In practical terms, whether or not NaI systems can accomplish a given measurement objective depends upon whether the data acquisition time, speed, and field of view can be optimized to achieve sufficiently low MDCs and meet the data quality objectives without compromising necessary spatial resolution of the data. MDCs are discussed in Section 5.4.

4.1.1 Guidance

- HPGe measurements for total uranium and Th-232 can be used for any investigation requiring data quality levels A or B
- HPGe measurements for Ra-226 can be used for any investigation requiring data quality levels A or B provided the measurements are corrected as explained in the "Ra-226 correction" topic (Section 5.6)
- NaI measurements may be used only for investigations where an ASL A data quality level is acceptable.

4.1.2 See Also

2.1 HPGe Systems and Measurements
2.2 RTRAK System and Measurements
2.3 RSS Systems and Measurements
2.4 Gator System and Measurements
2.5 EMS and Measurements
3.1 Predesign Investigations
3.1.2 Estimation of Above-FRL Excavation boundary
3.1.3 Above-WAC Detection, Confirmation, and Delineation
3.3.1 Hot Spot Evaluations
5.4 Minimum Detectable Concentration

4.2 DAILY ENERGY CALIBRATIONS

Energy calibrations are performed on each gamma spectrometry system both before and after deployment for field measurements, while efficiency calibrations are performed annually (See Sections 5.2 and 5.3). NIST-traceable radioactive standards containing Am-241, Cs-137 and Co-60 are used for the daily instrument performance checks that establish the proper energy calibration for each HPGe detector to be used on a given day. Once it has been established that the centroids for the three peaks trended for instrument quality control purposes are within ± 3 channels of the expected locations, the resolution and net counts for each peak are recorded and plotted on control charts to document that the instrument is operating as expected. The performance of the NaI systems is checked each day before and after use with radioactive sources containing Th-232 and its radioactive daughters Pb-212 and Tl-208. After ensuring that peak centroids are within ± 4 channels of their expected position in the spectrum, the resolution and net peak area of two prominent spectral peaks (a low energy peak and a high energy peak) are recorded and trended on separate control charts for each instrument. If a peak falls outside pre-established limits for its spectral position, the amplifier gain of the system in question is adjusted to return the peak centroid to the proper location (i.e., MCA memory channel) before the daily performance check is completed and the instrument is dispatched to the field. Daily energy calibrations and system performance checks for the HPGe and NaI detectors are performed in accordance with the RTIMP Operations Manual (Procedure RTIMP-M-003).

4.2.1 Guidance

- Perform energy calibration checks on *in situ* gamma spectrometry systems prior to use.

4.2.2 See Also

4.1 Data Quality Levels
5.2 Efficiency Calibrations of HPGe Systems
5.3 Efficiency Calibrations of NaI Systems

4.3 TIME REQUIRED TO COMPLETE SCANNING OF A REMEDIATION AREA

From a schedule perspective, two questions must be answered in order to plan an *in situ* gamma spectrometry measurement campaign:

1. How many measurements (HPGe) can be made in one day?
2. How long does it take to measure one acre of ground with either NaI or HPGe?

Assuming 100 percent efficiency and a data acquisition time of 5 minutes for HPGe measurements, then 96 measurements can be made in an 8-hour day. At a 1 m detector height, 96 measurements correspond to 99 percent coverage for two acres (Section 4.6). The number of NaI measurements that can be made in a single day depends upon the shape of the area to be scanned. It will require fewer measurements to cover a long narrow area than a shorter but wider area. Using the equations in Section 4.5.2, one can compute that it takes between 460 and 900 four-second measurements (30 to 60 minutes) to cover an acre of ground with an NaI platform at 1 mph, depending upon the degree of overlap and the number of back and forth traverses.

However, these ideal measurement performance factors are extremely unrealistic because time is needed for daily briefings and plans, pre-operational and post-operational QA/QC checks, instrument calibrations, transportation of equipment to and from the measurement area, moving and setup of equipment between measurements (HPGe), various tasks associated with working in radiologically controlled areas (such as donning and doffing PPE and frisking tools), and data reduction. In general, one to two acres of ground can be covered per day with either HPGe or NaI measurements.

4.3.1 Guidance

- Allow four hours per acre for mobile NaI measurements at 1.0 mph, and a 0.6 m overlap under good conditions, i.e., flat terrain with few obstructions.
- Assume 65 HPGe measurements (1.5 acres) per day in a non-radiologically controlled area, using a 5-minute count time and three instruments.

- Non-contiguous areas and partial coverage will take longer to measure by NaI than contiguous areas of the same size with full coverage.
- When work is performed in radiologically controlled areas, the estimated areal coverage figures given above should be reduced by 50%.

4.3.2 See Also

4.5 Detector Field of View and Area Coverage
4.6 HPGe Grid Configurations

4.4 FIELD MOISTURE MEASUREMENTS

Field measurements collected with the NaI and HPGe systems must be corrected for soil moisture to report the results on a dry-weight basis. This is done to allow a comparison between laboratory results (most always reported on a dry-weight basis) and real-time measurements. Currently, soil moisture measurements are performed in the field with either a meter that measures the dielectric constant of the soil, which is strongly dependent on the soil moisture content (the Dynamax moisture meter), or an infra-red radiation reflectance meter (Zeltex meter). For NaI measurements, a minimum of two soil moisture readings are collected per acre traversed by the NaI platform, whereas a soil moisture measurement is made at every location where HPGe data are collected. Soil moisture levels should be below 40 percent before NaI and HPGe measurements are made. Specific instructions, if any, will be found in area-specific PSPs.

4.4.1 Zeltex Soil Moisture Measurements

The Zeltex instrument is a portable device that measures the absorbance of infrared light by water in the soil and uses the degree of absorbance to quantitate soil moisture. It employs a tungsten lamp, near-IR-band-pass filters at four wavelengths, and a PbS sensor to measure the reduction of reflected light due to absorbance by the sample (i.e., the soil). These measurements are corrected with reference beam measurements made in sequence, which monitor wavelengths not sensitive to sample moisture, but which account for other variables such as sample surface condition, particle size and color. The difference in the sample and reference beam measurements is compared to a calibration curve loaded in the system computer, which converts absorbance readings to moisture content.

The system must first be calibrated using actual soil samples with a range of moisture contents determined by conventional methods, for example, by drying. Up to 50 calibration curves may be stored in the instrument memory for various soil types. Curves are chosen for use by selecting a channel number from one of the instrument menus. Soil moisture may be computed on the basis of either wet or dry

sample weight. For consistency with measurements made with the Troxler instrument, Zeltex calibrations are computed on a dry-weight basis.

There is very little penetration of the near IR radiation into the bulk material being measured. That is, the Zeltex instrument measures surface moisture. To obtain a moisture measurement that is representative of the bulk material from which gamma rays are being detected, the normal practice is to take Zeltex measurements at the soil surface and after removing two inches of soil. The two values are averaged to determine the moisture level for the location of the associated *in situ* gamma measurement. If needed, the Zeltex meter could be used to develop a soil moisture profile with depth.

Advantages of making soil moisture measurements with the Zeltex instrument include: the measurements do not require a radiation source that can interfere with NaI and HPGe measurements, precise measurements may be obtained in 6 sec, the instrument is relatively insensitive to ambient temperature, and the system is battery operated and field portable. Details on the operation of the instrument are provided in the RTIMP Operations Manual.

4.4.2 Dynamax Soil Moisture Measurements

The Dynamax soil moisture meter determines soil moisture by measuring the dielectric constant of the soil. This parameter is strongly dependent on the moisture content of the soil. The instrument has four stainless steel rods that are inserted into the soil to collect a moisture reading. These rods act as a waveguide along which the instrument propagates a microwave signal. By analyzing the reflected signal, the instrument determines the dielectric constant of the soil. The meter then calculates the soil moisture from the dielectric constant.

To obtain an *in situ* soil moisture reading, an analyst selects the appropriate soil type from one of the instrument menus, then simply inserts the stainless steel rods into the soil perpendicular to the soil surface and presses the "READ" button. The dry base soil moisture reading appears on an LCD screen in a matter of seconds. The operation of the Dynamax soil moisture meter is covered in detail in RTIMP Operations Manual. The Dynamax instrument has been calibrated for the soil types encountered at the Fernald site. The soil moisture reading from the instrument is characteristic of the volume bounded by the stainless steel rods that are inserted into the soil. Because these rods are three inches long, only a single Dynamax moisture measurement is required at each location, in contrast to Zeltex meter, which requires two moisture readings at each location. Like the Zeltex meter, Dynamax readings on frozen soil are not valid.

The advantages of using the Dynamax meter to perform soil moisture measurements are similar to those of the Zeltex meter: it is battery powered and light weight; it does not require radioactive sources that could interfere with the gamma spectrometry measurements; and it is insensitive to variations in environmental conditions. However, it does require contact with the ground surface, and could become contaminated.

4.4.3 Guidance

- Surface soil moisture measurements will be obtained at the center point of each HPGe measurement.
- A minimum of two soil-moisture measurements per acre will be taken for NaI measurements.
- If soil moisture measurements are not available for a given day, values will be estimated based upon measurements made in areas nearest to those on which *in situ* gamma spectrometry measurements were performed (provided that no rainfall has occurred in the intervening time period).
- If differences in weather conditions preclude the use of moisture data obtained on other days and in other areas, a default value of 20 percent soil moisture will be utilized. The default value will overcorrect (i.e., yield higher results) in dry conditions, and will undercorrect (i.e., yield lower results) in wet conditions.
- Do not perform *in situ* gamma measurements when the soil moisture exceeds 40 per cent. This is likely to be the case for several hours following a heavy rain.
- Do not perform *in situ* gamma measurements on days when a measurable accumulation of snow has fallen.
- Do not perform *in situ* gamma measurements if standing water obstructs a significant portion of the detector field of view. Consult Section 4.11 for more specific guidance.
- When using either the Zeltex or the Dynamax instrument, ensure that the proper calibration curve is used for the type of soil being measured.

4.4.4 See Also

4.11 Surface Conditions and Topograhic Effects
4.12 Environmental Influences on *In Situ* Gamma Spectrometry Data
5.5 Moisture Corrected Data

4.5 DETECTOR FIELD OF VIEW AND AREA COVERAGE

The field of view of a stationary detector is defined as the surface area that corresponds to the volume of earth from which 85 to 90 percent of the detected gamma photons originate. For detectors in general, the field of view primarily depends on the height of the detector above the ground surface and the energy of the incident gamma photon. Detectors farther from the ground surface will have larger fields of view than detectors closer to the ground surface. Because higher energy gamma photons are less attenuated by soil

and air than lower energy photons, the field of view is larger for higher energy photons than for lower energy photons (Miller, et. al., 1994).

Area coverage refers to the area seen by a detector if the detector platform is in motion during data collection. The HPGe detectors collect data in a stationary mode, and the area coverage is equal to the field of view of the detector. However, NaI measurements are made in a mobile mode, and the NaI field of view is translated parallel to the direction of movement to yield an area that is larger than the field of view of a stationary detector.

4.5.1 HPGe Detectors

Table 4-1 summarizes the field of view for HPGe detectors as a function of height. The field of view is dependent upon gamma photon energy. Therefore, the values in Table 4-1 represent an approximation for all gamma photons; however, the field of view will be somewhat larger or smaller for higher or lower energy gamma photons, respectively (Miller, et. al., 1994).

Figure 4-1 plots the cumulative uncollided photon fluence versus distance from a point on the ground directly beneath the center of the detector for 1,000 keV gamma photons (see Figure 1 in Miller et al. for more information on photon fluence). Two curves are displayed in this figure – one for a detector at a height of 100 cm and another for a detector set at a height of 31 cm. About 28 percent of the gamma photons impinging on the detector, which is 100 cm above the ground, originate from the soil inside a circle with a radius of one meter centered on the point on the ground directly below the center of the detector. For the same detector, approximately 55 percent of the gamma flux comes from within a two-meter circle, and about 86 percent originates from within a six-meter circle. The corresponding percentages for a detector 31 cm above the ground are all higher: 63% at one meter, 81% at two meters and 94% at six meters. Figure 4-2 provides a two-dimensional cross section of photon fluence as a function of soil depth and distance from the detector. Each cell (which in three dimensions is actually a ring that surrounds the detector) represents a volume from which one percent of the total uncollided gamma photons impinging upon the detector originate. The practical significance of Figure 4-2 is that HPGe detectors at a height of 100 cm primarily register gamma photons from the top 10 to 15 cm of soil within 2 m of the detector. The same is true for a detector set at a height of 31 cm.

4.5.2 NaI Detectors

The detector height for all NaI platforms, except the EMS, is fixed at 31 cm. One might intuitively expect the NaI detectors to have a field of view similar in size to the 31 cm HPGe field of view shown in Table-4-1, i.e. a circular area of radius 2.5 m. Measurements were made to determine the field of view of each 4"x4"x16" NaI detector used at the FCP. These measurements demonstrated that the fields of view

of the various NaI instruments were very similar, and that the RTIMP would be justified in using a similar value, 16.6 square meters, for all the mobile NaI platforms (i.e., the area of a circle of radius 2.3 m) for 1000 keV photons. It makes sense on physical grounds that the experimentally determined field of view of the NaI detectors turned out to be slightly smaller than the HPGe field of view for the same detector height because the vehicles and the tires on which the NaI detectors are deployed will act as shielding and attenuate some of the gamma rays that would otherwise strike the detector. The reduction in the radiation that strikes the NaI detector, although actually caused by photon scattering and absorption by the vehicle, may be thought of as resulting from a slightly smaller detector field of view. This effect would be most pronounced for the RTRAK, which has large tires; but the measurement data for the RTRAK are not markedly different from data for the other detectors.

NaI measurements are usually collected in a mobile mode, and therefore the area scanned during a 4-second measurement is larger than the stationary field of view quoted above. The measurement coverage area will vary with count time and scanning speed, as illustrated by the examples in Table 4-2. Faster scanning speeds and/or longer count times will result in larger single-measurement viewing areas. The computational method for determining the area covered by mobile NaI measurement is illustrated on Figure 4-3, using the standard operating speed of 1 mile per hour and a 4-second count time.

The general approach to scanning a remediation area with a NaI instrument is to make adjacent back and forth traverses until the area of interest has been covered as completely as possible. A gamma spectrum is collected every 4 seconds to derive U-238, Th-232 and Ra-226 activities as a function of location. Figures 4-4 and 4-5 show the degree of overlap typically involved in scanning a land area with a mobile NaI instrument. These figures illustrate that there is usually some overlap between adjacent passes, as well as overlap between successive measurements in the same pass. The equation below has been developed to estimate the total area covered by a given number of passes with a specified number of measurements in each pass:

$$A_{TOT} = k \times \left[0.8941 \times n \times v \times r \times t + 3.1416 \times r^2\right] - (k-1) \times \left[0.4471 \times n \times v \times L \times t + L^2\right]$$

where:

n = number of measurements in a pass
k = number of passes (each pass is assumed to have the same number of measurements)
r = radius of the field of view in meters (2.3 m for the NaI systems as 31 cm height)
v = platform speed in miles per hour
t = data acquisition time in seconds
L = Amount of overlap in meters between adjacent passes
kn = total number of measurements

The average area per measurement is then given by

$$A_{AVE} = A_{TOT}/kn.$$

Table 4-3 provides some numerical examples, computed with the equations above, using standard NaI operating conditions of one mile per hour scan speed, 4-second single spectrum acquisition time and 0.4 meter overlap between passes were assumed. Greater overlap will reduce the areal coverage below the values shown in Table 4-3. Table 4-4 illustrates the effect that varying the amount of overlap between adjacent NaI passes will have on the total area covered.

4.5.3 Guidance

- For general survey measurements with HPGe detectors, a 100 cm detector height should be used.
- In areas where contamination is homogeneous, very similar results will be obtained at different detector heights.
- In areas where contamination is very heterogeneous, different results may be obtained at different detector heights. In fact, varying results at different detector heights is an important means of recognizing a heterogeneous distribution of contamination.
- Whereas the HPGe field of view is circular, the area covered by a 4-second NaI measurement resembles an elongated ellipse because the platform moves while the measurements are being performed.
- The field of view for NaI detectors has been experimentally determined to be 16.6 m^2. Vehicle shielding is different for each NaI system; but this effect is minor, with all NaI systems having the same size field of view, practically speaking.
- Unless special circumstances dictate otherwise, use a 0.6 meter overlap on all adjacent passes while scanning with NaI platforms. Such an overlap corresponds to a separation of the center line of the passes of 4 m. Overlap is desirable because this decreases the probability of failing to detect radioactivity at the outer edge of the field of view on a particular traverse with a mobile NaI instrument.
- Shielding effects caused by the NaI platforms are minimized by alternating back and forth passes with overlap.
- Data in Table 4-4 can be used to calculate the theoretical area represented by a given number of aggregated measurements. For example, at 1 mph, a 4-second data acquisition time and a 0.6 m overlap, if 100 measurements are aggregated for mapping purposes then the area represented by the 100 measurements is 100 (16662/2250) = 741 m^2.
- In reality, the area represented by an aggregated number of measurements could be significantly larger or smaller than the area calculated above, depending upon driver skill in maintaining a constant speed of one mile per hour and straight-line paths with the same degree of overlap on all passes.

4.5.4 See Also

4.3 Time Required to Complete Scanning of a Remediation Area

4.15 Mapping Conventions

4.6 HPGe GRID CONFIGURATIONS

When HPGe systems are deployed to measure the activity of radionuclides over a sizable area, a triangular grid pattern is used to establish measurement locations. The grid may be set up with varying degrees of overlap in the field of view to achieve the desired coverage level, with the number of measurements per acre increasing as coverage goes from 90 to 100 percent. Figure 4-6 displays the detector field of view as circles having a specific radius, and these circular areas represent the ground surface from which 85 to 90 percent of the detected photons originate (Figure 4.2).

As noted in the protocols listed in Section 3.0, the standard operating procedure is to configure a triangular grid on 11-m or 4-m centers for 100-cm and 31-cm detector heights, respectively. This corresponds to area coverage of 99 percent for both detector heights. Standard operating practice is to use 31-cm measurements to verify and determine the boundaries of hot spots and above-WAC uranium contamination.

4.6.1 Guidance

- HPGe measurements at a detector height of 100 cm will be set up on a triangular grid with 11-m centers to obtain 99 percent coverage. This coverage is sufficient for Phase I of the predesign and precertification measurements.
- HPGe measurements at a detector height of 31 cm will be set up on a triangular grid with 4-m centers to obtain 99 percent coverage. Perform 31 cm HPGe measurements when verifying the presence of elevated contaminant levels and determining their boundaries.

4.6.2 See Also

3.1 Predesign Investigations
3.3 Precertification Investigations
4.5 Detector Field of View and Area Coverage

4.7 HPGe DATA ACQUISITION TIME

In general, performing longer counts will reduce both measurement uncertainties and minimum detectable concentrations. Performing shorter counts will allow more HPGe measurements per day. However, if the count times are too short, the validity of the results could be compromised. The data in Table 4-5 demonstrate that five-minute data acquisition times with HPGe detectors give results that are very similar to those obtained with fifteen-minute count times. This is true for the three detector heights commonly used for *in situ* measurements at the FCP. The five-minute results generally satisfy all of the data quality requirements for the isotopes of interest, even at fairly low levels. The measurement results displayed in

Table 4-5 were obtained from one location over a six-day period in November 1997. The results demonstrate that:

1. There is little difference between the means of 300- and 900-second results for a given isotope at a given detector height for U-238 (or total uranium), Th-232, Ra-226 and K-40.
2. There is little difference between the means of 15- and 31-cm results for a given isotope at a given count time, thus demonstrating that 15-cm measurements should be needed only rarely.
3. Although results for measurements made at 100 cm are generally slightly lower than those obtained at 15- and 31-cm, the difference is less than 10 percent for total uranium, less than 5 percent for Th-232 and K-40, and less than 3 percent for Ra-226.

4.7.1 Guidance

- Five-minute count times, irrespective of detector height, may be used for detecting, confirming, and delineating WAC exceedances and hot spots.

4.7.2 See Also

4.5 Detector Field of View and Area Coverage
4.9 Detection of Above-WAC Uranium Contamination

4.8 TRIGGER LEVELS

A trigger level is defined as a specified radionuclide activity that, if exceeded by a NaI or HPGe measurement, requires subsequent specific actions to be taken. These actions may include, but are not limited to excavation of soil, additional *in situ* gamma spectrometry measurements, or collection and analysis of physical samples. The RTIMP has established WAC trigger levels to aid personnel making decisions on waste disposition issues. The numerical value of the WAC trigger level for uranium is presented below, along with an explanation of how it was derived.

WAC trigger levels have been established to aid personnel in making a conservative decision regarding proper waste disposal. In this regard, the only waste disposal decision being made on the basis of *in situ* measurements is whether or not the soil at a particular location exceeds the uranium WAC for the OSDF. Trigger levels have not been established for FRL or hot spot criteria because exceedance of these criteria does not affect disposal of the soil in the OSDF, provided the exceedance is below any applicable WAC. FRL and hot spot criteria come into play during the precertification and final certification of an area. However, in this instance, decisions are ultimately made on the basis of physical sampling and analysis.

All measurements have some associated uncertainty, and so any measurement is at best an estimate of the true value of the measured quantity. It is good practice to specify the uncertainty along with a result so that one can establish a range inside which the true value lies with some desired degree of certainty. Trigger levels are established below the actual regulatory limit to avoid inadvertently exceeding the limit in the event that the true value actually lies at the upper end of the stated experimental range. Thus a trigger level provides a margin of safety that compensates for our imprecise knowledge of the true value. The general approach described below can be applied to any analytical method/data set, but the tables provided are specific to the HPGe and NaI instruments used at the FCP.

As noted above, trigger levels are set below the actual regulatory level to reduce the chance of mistakenly classifying soil as meeting the limit when it actually does not. The difference between the regulatory limit and the trigger level is a function of the precision (total system uncertainty) of the measurement being performed and the required level of confidence that a measurement at or below the trigger level will not exceed the regulatory limit. Because the precision of a measurement method is radionuclide specific, the trigger level will also be radionuclide specific. The trigger level is defined as:

$$\text{Trigger} = L - k\sigma_{limit} \qquad \text{Equation 1}$$

where:

- L = the magnitude of the limiting criterion, in this instance, the OSDF WAC
- k = the standard normal variate; a statistical factor related to the acceptable confidence level of the measurement. At the 95 percent confidence level, k is equal to 1.645 for a single-tailed distribution.
- σ_{limit} = the standard deviation of measurements of soil concentrations that are numerically equal to the limit

Several factors are important in establishing trigger levels for HPGe and NaI systems. First, a 95 percent confidence level for a one-sided distribution ensures that the regulatory limit will not likely be exceeded. Second, the trigger levels presented below are most applicable when the area of the potential WAC exceedance is approximately the same size as, or larger than, the field of view of the detector. The trigger levels are less reliable as the size of the potential regulatory exceedance decreases below the area of the detector field of view. This situation is discussed in Section 4.9. Also, from a practical perspective, a trigger level cannot be less than or equal to either the typical background concentration of a given radionuclide or to the detection limit for that nuclide. Ignoring these criteria when establishing trigger levels creates the risk of frequent false-positive trigger level exceedances.

4.8.1 HPGe Trigger Levels

The HPGe trigger level for an exceedance of the uranium WAC at a data acquisition time of 5 minutes is shown in Table 4-6 (calculated using Equation 1). The standard deviation representing overall HPGe precision is taken from information in Tables 2-2 and 2-3 in the January 1999 Comparability Study (DOE 1997a). Data from Tables 2-2 and 2-3 of that report are based on nearly a full year of HPGe measurements performed at the RTIMP field quality control station (FQCS) 15, which was located north of the now excavated old sewage treatment plant.

The mean and the uncertainty for the FQCS-15 measurements are: 93.4 mg/kg ±5.96% for total uranium, 1.14 pCi/g ±5.83% for Th-232, and 1.05 pCi/g ±9.5% for Ra-226 (afternoon measurements). Based on a smaller number of measurements, overall HPGe system uncertainties for 5-minute counts were determined to be 7.33% for total uranium, 7.17% for Th-232 and 11.69% for afternoon Ra-226 measurements. The assumption is made that the above estimates of total HPGe system uncertainty are also valid at more elevated concentrations than were measured at FQCS-15 (this is a conservative assumption as the counting error will decrease in a relative sense as the concentration increases).

4.8.2 NaI Trigger Levels

NaI WAC trigger levels are calculated for each NaI system using counting data obtained from measurements performed on the RTIMP calibration pad with the complete set of 45 uranium sources deployed. This experimental arrangement approximates the gamma ray flux from an area uniformly contaminated with 980 mg/kg uranium, a level very near the uranium WAC of 1030 mg/kg. The NaI trigger levels are calculated when an instrument is calibrated. The methodology and equations for computing NaI trigger levels are described in "Measurement Uncertainties and Minimum Detectable Concentrations for the *In Situ* NaI Gamma Spectroscopy Systems used at the Fernald Site" (ANL 2004). The most recently determined WAC trigger levels for each of the NaI systems is provided in Table 4-7. These values are updated annually, when each detector is calibrated. The RTIMP group has set 875 mg/kg as the minimum uranium WAC action level for a 4-second count with any of the 4"x4"x16" NaI systems, and as a conservative measure this action level is used to initiate further WAC investigation with an HPGe system.

4.8.3 Guidance

- HPGe detectors are capable of detecting radioactivity at levels well below the WAC concentration of 1,030 mg/kg total uranium. Five-minute HPGe MDCs are also below FRL levels (except the 10 mg/kg uranium FRL).
- When a measurement exceeds a trigger level, actions must be initiated just as if the regulatory limit itself was exceeded
- HPGe detectors can recognize WAC exceedances if the area of the exceedance is at least 50 percent of the detector field of view at a given height and the total uranium concentration is at least 1500 mg/kg. Identification of WAC exceedances becomes less reliable if the area of high contamination is smaller and/or the uranium concentration is close to 1030 mg/kg.
- WAC trigger levels for NaI systems have been developed for each platform, and they are all greater than 875 mg/kg. So, to be conservative, this value is used for the WAC action level for any NaI system.

4.8.4 See Also

3.1.3 Above-WAC Detection, Confirmation and Delineation
3.2.2 Excavation Control for Lifts
4.9 Detection of Above-WAC Uranium Contamination

4.9 DETECTION OF ABOVE-WAC URANIUM CONTAMINATION

Trigger levels calculated in Section 4.8 for above-WAC uranium contamination are designed for uranium contamination near 1,030 mg/kg over an area that approaches or exceeds the area corresponding to the detector field of view. However, while conducting the HPGe and RTRAK Comparability Studies, and remedial operations in various areas of the Fernald site, highly contaminated areas that were significantly smaller than the detector field of view were encountered. Table 4-8 lists the HPGe action levels for total uranium as a function of detector height for a given contamination area where uranium levels exceed the WAC. Action level is defined here as a uranium concentration that, if exceeded by a NaI or HPGe measurement, indicates the need for further HPGe measurements centered on the contamination area to determine if the uranium WAC trigger level is exceeded for the measurement area.

The action levels in Table 4-8 are calculated based upon the percentage of photons impinging upon the detector as shown in Miller et. al. (1994, Figure 1) and in Figure 4-1 of this report. These calculations assume the hypothetical WAC exceedance area is centered directly below the detector and that all soil surrounding the WAC exceedance area has background uranium values. Thus, the action level will reflect the dominant photon fluence coming from the WAC material. In this case, the action level is simply the percentage photon fluence (as determined from Figure 4-1 using the uniform depth distribution

model) times the total uranium WAC level of 1,030 mg/kg. The action levels in Table 4-8 have been rounded downward to build in extra conservatism. They are meant to screen areas smaller than the detector field of view for possible WAC exceedance. Typically these suspected WAC exceedances will have been identified by some other means; for example, by visual recognition of exposed product, construction rubble, soil discoloration, or by frisking with a hand-held survey meter.

4.9.1 Guidance

- Frisk the suspect objects and areas with a hand-held GM survey meter to delineate the zone of elevated activity and estimate its area.
- Place the HPGe detector over the center of the area of elevated activity.
- Use Table 4-8 to choose uranium concentration levels that are representative of the size of the suspect area when evaluating WAC exceedance areas smaller in size than 66 percent of the field of view. For example, suppose a hand-held survey meter indicated an area of elevated activity having a radius of 1.5 m. If an HPGe measurement at a detector height of 100 cm yielded a total uranium concentration greater than 400 mg/kg, a WAC exceedance is possible. If a 31-cm HPGe measurement of this area was performed instead of the 100-cm shot, the corresponding action level would be 880 mg/kg.
- Consult the RTIMP group if smaller areas of suspected above-WAC contamination are to be measured.
- It is not realistic to expect to detect small areas (e.g., less than 1 square meter) of radioactive material exceeding WAC with HPGe. Note that the chance of collecting such material with physical samples at randomly chosen locations is also extremely small.

4.9.2 See Also

3.1.3 Above-WAC Detection, Confirmation and Delineation
4.10 Use of Hand-Held Survey Meters

4.10 USE OF HAND-HELD SURVEY METERS

Hand-held survey meters, some versions of which are commonly called friskers, can be useful tools for identifying the presence of radioactivity in soil at the FCP. The advantages of a hand-held survey meter include low cost, ruggedness, small size, and ease of use. This type of instrument is effective for quickly assessing the general level of contamination of debris or other objects, samples, or small areas of concern such as discolored soil. It would be very time consuming to use this type of instrument to scan soil areas of even moderate size because the instrument probe must be placed close to the surface, giving it a very limited field of view. Another disadvantage of these instruments is that they cannot provide isotope specific information. They only measure gross alpha or beta/gamma activity, and the instrument response

to gamma photons from different radionuclides can vary widely. Thus, the gross activity reading cannot be converted to quantitative radionuclide concentrations or even indicate if multiple isotopes are present.

Despite the above limitations, a simple survey meter or a sensitive dose rate meter provides a reasonable overall measure of contamination. Where a reading is observed to be in excess of normal background, it indicates elevated radionuclide levels, and thus a potential hot spot or WAC exceedance. If a single radionuclide is known to be present, a rough conversion from count rate to concentration can be determined. At sufficiently elevated radionuclide levels, survey meters are quite sensitive and capable of delineating the area of contamination when used in a scanning mode.

Two hand-held instruments that can be used to support real time soil measurements are the Bicron MICRO-REM meter and a Ludlum GM probe and rate meter. Their uses are described in more detail in the following three sections.

4.10.1 Micro-Rem Meter

The MICRO-REM meter employs a tissue-equivalent scintillator as a detector element. This meter has a fairly constant response to gamma radiation of varying energy and good sensitivity at background levels. It provides a reading of the external dose rate (which is closely related to the exposure rate for environmental radiation fields) from all gamma-emitting sources present. When held at waist height, it essentially sees the same radiation field as a HPGe at one meter above the ground. It responds to both primary and scattered radiation, so it's reading is generally proportional to the total count rate (peaks + continuum) in a HPGe or NaI spectrum. It is used in two ways to support the real time instrument program:

- To identify potential external radiation interference when using *in situ* spectrometers
- To serve as a quality control measurement to confirm the relative radiation intensity at spectrum measurement locations.

4.10.2 GM Survey Meter (Frisker)

The GM survey meter (frisker) consists of a nominal 2-inch diameter Geiger-Mueller pancake probe (gas-filled detector) and a rate meter. This probe responds to typical beta radiation with an approximate efficiency of 10 percent (at the FCP, the efficiency is 3 percent for beta particles emitted from protactinium-234) and to gamma radiation with an approximate efficiency of 1 percent. The probe can be held in the hand or attached to a pole to access areas that cannot be reached with the arms. Because of its

sensitivity to beta radiation, it is most effective when held close to a measurement surface (approximately one half inch). It can be passed over the surface using a scan rate of about 1 to 2 inches per second. Areas with surface activity of 1,000 disintegrations per minute (dpm) per 100 cm^2 are readily detectable with this instrument. To support real time soil remediation measurements, the GM survey meter can be used to:

- Locate the highest activity in an elevated area (potential hot spot or WAC exceedance) to guide the "centering" of an HPGe or NaI measurement;
- Investigate suspicious objects or small areas that are identified visually;
- Scan cores or sections of soil sampled with devices such as the Geoprobe
- Scan areas that are inaccessible with either the NaI or HPGe detectors, such as steeply sloped surfaces or the bottoms of very narrow trenches.

4.10.3 Use of Alpha and Beta/Gamma Friskers

Separate from their use to support soil remediation, alpha and beta/gamma friskers are used in a Safety and Health role to identify unusual conditions or unexpected radionuclide mixtures that may require increased personnel protective measures. Many of the radioactive daughters of U-238 and Th-232 are alpha emitters, Th-230 is one of the more significant of these daughters from a health and safety perspective. Th-230 has a characteristic gamma emission with an energy of 67.7 keV that can be used to quantify it; but it is a weak emission in comparison to other gamma rays from U-238 and Th-232 daughters. The RTIMP HPGe detectors have a Th-230 detection limit of approximately 55 pCi/g for a five-minute count.. Since the presence of Th-230 in the soil is not easily recognized by gamma detectors until levels become rather high from a health physics perspective, Health and Safety personnel use alpha and beta/gamma friskers to infer the presence of Th-230. Elevated readings on an alpha frisker or ratios of beta/gamma frisker to alpha frisker readings less than 2 can be an indication of significant Th-230 levels. But these indicators must be confirmed with HPGe measurements, usually requiring longer than normal count times. The general decision process that is followed in potential Th-230 areas at the FCP, when friskers are used in combination with HPGe measurements, is illustrated on Figure 4-7. When beta/gamma activity is less than two times the alpha activity, additional PPE is required while performing the HPGe measurements to check for the presence of Th-230.

The friskers currently being used at the FCP consist of a Ludlum model M3 equipped with either a pancake GM probe (gas-filled detector) for beta/gamma measurements or an alpha probe (scintillation detector). Measurements are made by passing the probes over the surface of the soil or debris at a rate of 3 cm/second and at a distance of 0.6 cm or less. Close scanning of the soil surface is particularly

important for alpha detection, as alpha particles are rapidly attenuated by interaction with air molecules. The friskers are calibrated to read out in counts per minute (cpm) for either alpha or beta/gamma radiation. While the devices register only gross activity, comparisons of alpha and beta/gamma readings during excavation may provide some useful information regarding the nature of the source of radiation. However, one must be very cautious about the use and interpretation of alpha radiation readings from very rough surfaces.

Beta/gamma friskers are also used in the soil remediation program in locations where there is cause to suspect the presence of above-WAC material. These areas are generally of limited extent. Experience has shown that discolored soil, visible uranium production compounds and the presence of prohibited items (i.e., items that cannot be placed in the OSDF) oftentimes will he accompanied by small volumes of above-WAC soil. A frisker reading of 200,000 decays per minute (dpm) of beta/gamma activity has been established as a trigger level for the possible presence of above-WAC uranium. When friskers indicate the potential for above-WAC material and/or Th-230 contamination, confirmation measurements are made with the HPGe instruments. If the frisker readings indicate that the area of the WAC exceedance is likely to be less than the HPGe measurement field of view, the HPGe detector height should be lowered to match its field of view to the size of the WAC exceedance. Removal of small areas of above WAC soil may be verified with an HPGe measurement at a reduced detector height or by "frisking" the area and applying the 200,000 dpm criterion.

The soil remediation program also uses the beta/gamma frisker to evaluate debris and other small objects (e.g. cement, rocks, soil cores, soil samples, etc.) for potential WAC exceedances. Friskers were used extensively to screen soil cores extracted from Area 2 Phase I in the vicinity of suspected above-WAC uranium contamination. After screening, the cores were divided into 260 soil samples and analyzed for total U. The results from this work indicate that the GM survey meter (i.e. frisker) can provide a good qualitative indication of the presence or absence of uranium at or above its WAC level for small objects such as these. In general, corrected counts per minute GM survey readings (ccpm, equal to sample count rate minus background count rate) less than 450 indicate that uranium concentrations are below WAC concern. GM survey readings above 1000 ccpm almost always indicate total uranium concentrations above WAC levels. GM survey readings between 450 and 1000 ccpm indicate the potential for WAC problems. One disadvantage of using GM survey meters to judge WAC compliance is that the one conducting the survey will be unable to recognize when the readings are caused by elevated levels of Th-232 and/or Ra-226 instead of U-238. The hand-held nanoSPEC system would be of use in such situations because it may provide qualitative isotopic information in addition to the count rate data.

Using the 450/1000 ccpm guideline, the GM survey meter can be used to screen small discreet objects (i.e., soil cores, items of debris or soil discolorations with diameters of one foot or less) for above-WAC contamination. HPGe or NaI instruments do not properly evaluate such small discrete objects because they are smaller than the field of view of the detector being used. (See Section 3.3.1.1, 4.8 and 4.9 for a more complete discussion of topics related to instrument readout versus the size of the contaminated area.) For objects where frisker results are ambiguous and WAC material is a potential concern, the use of the frisker should be supported either with discrete sampling or HPGe measurements at a reduced detector height. At this time, there is insufficient evidence to support the use of the GM survey meter for identifying hot spots or above-FRL areas, or for estimating the approximate lateral extent of these areas.

4.10.4 Guidance

- Use GM survey meters (i.e. friskers) as a quick check of the radioactivity level of discrete objects such as debris, soil samples, soil cores, or small discolored spots in the soil to determine the presence or absence of WAC material. Use the 450/1000-ccpm rule as a guide (less than 450 ccpm - no WAC concerns, 450-1000 ccpm - potential for WAC concerns, greater than 1000 ccpm - definitely WAC concerns).
- Beta/gamma readings exceeding 200,000 dpm indicate the possible presence of above-WAC material. The presence of above-WAC uranium is confirmed with HPGe measurements provided the contaminated area is large enough to obtain reliable HPGe results.
- Although no specific corrected counts per minute guidelines can be provided for recognition of hot spots using the GM survey meter, an HPGe measurement can be made in any area where frisker readings are anomalous, regardless of the meter reading.
- Use the 200,000 dpm beta/gamma activity cutoff to determine a rough boundary for above-WAC material, particularly when it is believed that the above-WAC area is smaller than the field of view of NaI or HPGe detectors. Also use this criterion to verify removal of small above WAC areas.
- Use the GM survey meter to help refine the location of greatest activity so that HPGe measurements or discrete soil samples may be obtained there.
- Use the MICRO-REM meter in conjunction with the NaI and HPGe systems to screen for possible shine effects, and to assist in evaluating anomalies in NaI or HPGe spectra.
- Alpha and beta/gamma friskers support Safety and Health measures by helping to identify high beta/gamma or Th-230 areas.
- The presence of Th-230 is suggested by beta/gamma activity that is less than two times alpha activity.

4.10.5 See Also

3.1.3 Above-WAC Detection, Confirmation, and Delineation
3.2.1 Above-WAC Excavation
3.2.2 Excavation Control for Lifts
3.3.1 Hot Spot Evaluation
4.9 Detection of Above-WAC Uranium Contamination
5.8 Contaminant Heterogeneity

4.11 SURFACE CONDITION AND TOPOGRAPHIC EFFECTS

Topographic effects need to be assessed to determine the appropriateness of using standard field calibration factors for real-time spectrometry measurements. The result of an *in situ* measurement performed with the HPGe or NaI systems depends on the fluence rate, i.e., the number of photons incident per unit area per unit time. This quantity can be directly related to the amount of radioactivity (activity per unit mass) in the volume of soil being measured and the position of the instrument with respect to the soil surface. Calibration factors derived for the standard *in situ* measurements utilize the concept of an infinite half-space; that is, a volume of soil that extends infinitely deep below a detector and out to the horizon at infinity. This flat geometry is analogous to a standardized counting geometry used for laboratory gamma spectrometry measurements, except that the *in situ* "sample" is very large and the detector is further away from the sample surface. Due to soil and air attenuation of the photons, the amount of soil being measured is finite in size, and the detector response varies with the height of the detector above the ground. The following sections will address potential departures from this idealized half-space geometry (i.e., deviations from a flat soil surface) as they relate to producing bias in the measurements.

4.11.1 Surface Cover

One of the factors to consider is the density of grass and brush covering the surface. Dense vegetation may shield the underlying soil and attenuate the photon fluence arriving at the detector, resulting in a low bias to the measurement. To ascertain the attenuating effect of grass on gamma photons, HPGe measurements were performed in grass of different heights at detector heights of 100 cm and 31 cm. Initially, the test location was covered by 105-cm (41.5-inch) high grass (average grass height within the field of view of the detector). Subsequent measurements were then performed at the same detector heights after the grass was cut to an 8-cm (3-inch) height, and the cut grass was removed before the HPGe measurements were collected. Results from this study are shown in Tables 4-9 and 4-10.

Data in Table 4-9 indicate that the total uranium and Th-232 average values collected in waist high grass (41.5-inch) are lower relative to the average collected over 3-inch grass. However, the uranium results for the two grass heights can be considered similar based on the counting error. Potassium-40 results show no significant difference, but the average value for tall grass is greater than for short grass (possibly due to the incorporation of K-40 in the vegetation). In looking at the relative attenuation of low vs. high-energy gamma photons used to quantify U-238 (Table 4-10), the attenuation of low energy photons is not significant. The 63.2 keV photons appear to be attenuated a bit more than the 92.6 and 1001.1 keV photons. However, the overall attenuating effect of the 41.5-inch high grass is very minor and not of concern for *in situ* measurements. Similar conclusions were reached when wet and dry grass were compared. Based on these measurements, grass as tall as waist height has an insufficient mass per unit area to attenuate gamma photons significantly. Tall grass is more of an operational nuisance than a measurement problem.

Rubble (i.e., rocks, gravel, concrete debris, scrap metal and other materials associated with the demolition of buildings and concrete pads) that might cover the ground surface is of greater potential concern because these more dense materials can cause greater photon attenuation. It should be noted that rocks and concrete rubble do not necessarily represent a pure attenuating layer, in as much as they are likely to contain the same naturally-occurring radionuclides that are found in the soil, and they may also have surface contamination resulting from uranium production operations. However, rubble on or near the ground surface should be treated as a shielding layer when the contamination associated with the underlying soil is well above the natural background levels in rocks and soil. The presence of such rubble will attenuate the gamma rays emitted by the radionuclides in the soil and will produce a low bias in the results. Therefore, as much rubble as possible should be removed before performing *in situ* measurements. After removing as much rubble as possible, the detector should be positioned so as to minimize the field of view obstruction caused by the remaining rocks and/or rubble, especially near the center of the field of view of the detector. A strategy that can be helpful in this regard is to perform measurements at a lower detector height, which will reduce the areal extent of the detector field of view and thus result in more of the rubble being on the periphery of the field of view where its attenuation effects are much less important.

Snow or ice cover and standing water also act as attenuating layers, which could bias measurements low. In the case of snow, it is the water equivalent (again, in terms of mass per unit area) that is the fundamental controlling parameter. A 10-cm snow layer with a water equivalent of 1 cm (1 g/cm^2 surface layer) would bias results low by 33 percent at 100 keV and 19 percent at 1,000 keV.

A puddle (or any other surface object such as a rock) off to the side of a detector may not unduly influence a measurement. Figure 4-8 and the objects classified in Table 4-11 can be used to estimate the decrease in the gamma photon fluence at the detector as a function of the size of the area covered by water or rubble. Objects 4 to 8 m away, i.e., objects located somewhere in the outer ring (ring 9) on Figure 4-8, may cover 10 m^2 or more with no significant decrease in the fluence, whereas these same objects within 3 m of the detector would block a considerable portion of the gamma photons normally seen by the detector.

4.11.2 Example of Topographic Coverage Correction

As an example of a measurement location where one should consider the need for corrections to the measurement results because of the presence of objects that could significantly attenuate the gamma flux, consider a case where there is a puddle of water, a large tree trunk, and a pile of excavated clean soil (a wall, in effect) near a measurement point. Assume that the natural background content of the soil in the excavation wall is well below that of the contaminated area to be measured. All three "objects" obstruct some fraction of the full ground area normally seen by the detector. The characteristics of these objects are given in Table 4-11. Offhand, this information might be grounds to disqualify this location as inappropriate for using the normal detector calibration. However, mapping these objects and overlaying the fluence rate cell chart from Figure 4.8 allows for a realistic evaluation of the situation. This has been done in Figure 4-9. As a conservative estimate, the water in the puddle is considered to be deep enough to absorb all of the photons originating in the soil beneath it. Table 4-12 summarizes the fluence reduction for all objects, broken down according to the ring in which they fall (ring 1 being the center and ring 9 being the outer most). Note that the tree blocks the part of the cell it covers and also shadows the same fraction of each cell beyond it in the outer rings. The total fluence reduction is seen to be 15 percent, which is not unduly large. Because the objects in the field of view prevent photons from reaching the detector, the true result will be larger than the measured result. The multiplicative correction that should be applied to the measured radionuclide concentration at this location would be 1/(1.0 - 0.15) or 1.18.

As previously pointed out, those planning *in situ* measurements should consider whether any non-soil objects in the detector's field of view should be considered part of the contamination to be evaluated. Depending on how that issue is decided, removal of these objects may not be necessary. There may also be occasions when a significant portion of a measurement field of view contains soil with the radionuclides of concern near background levels, with the remaining portion of the field of view

containing elevated radionuclide concentrations. This could occur near remediation area boundaries or near excavation walls or soil piles previously determined to be at or near background. Both the contaminated soil and background materials will emit the same gamma rays, and one should be concerned that the presence of the background material will produce a low bias in the measurement results. Under these circumstances, it is appropriate to treat the background material as part of the source, but to compensate for its diluting effects. If the radionuclide concentration of the "background" soil within the field of view of the detector is known, then the following generalized equation can be applied to correct measurement results for this dilution effect:

$$C_c = (C_m - xC_b)/(1-x)$$

where: C_c = the concentration of the contaminated portion in the detector field of view,

C_m = the measured concentration,

C_b = the background concentration, and

x = the fraction of the fluence at the detector associated with the background area.

4.11.3 Density

Variations in soil density do not result in significant changes to *in situ* measurements of radionuclide activity because the density term appears in the numerator and denominator of the detector calibration factor, which converts count rate to activity per unit mass of soil, and cancel out. However, soil density does influence the depth of soil that will completely attenuate the gamma photons. Less dense soil will attenuate fewer gamma photons, and thus, the detector can "see" photons emitted from deeper regions of the soil profile. At the FCP, the detector depth of view is calculated using a typical soil density of 1.5 g/cm^3.

4.11.4 Slope of Ground Surface

Measurements can be performed on a sloped surface by maintaining the long axis of the NaI detector parallel to the surface and the HPGe detector axis perpendicular to the surface. For slopes less than 33 percent (1 vertical for 3 horizontal), most of the NaI and HPGe platforms can be used to obtain the measurements. However, when the slope is steeper than 33 percent, NaI measurements may be limited to the use of the EMS platform. The HPGe tripod platform can be secured with rope to accommodate some increase in slope, but slopes in excess of 100 percent (45 degrees from the horizontal) will require the use of the EMS for HPGe measurements.

The tripod-mounted HPGe detector can be adjusted to incline at a different angle than that of the ground slope because a slight inclination does not produce a significant change in the result. Calibration measurements performed with an HPGe detector indicated that a full 90-degree tilt (axis of Ge crystal parallel to the ground instead of perpendicular to the ground) changed the result by 5 to 10 percent. Note that this is not an issue for NaI detectors because their orientation relative to the vehicle is fixed and their long axis is always parallel to the surface when measurements are performed.

4.11.5 Ground Roughness

In a recent publication (Laedermann, et. al., 1998), the effects of ground roughness on *in situ* spectrometry results were examined using a model that incorporated closely spaced bumps in the terrain. It was concluded in this study that bumps of up to 20 cm in height (the largest studied) were negligible when there is a homogenous distribution, (i.e., constant with regard to depth and horizontal position) of radionuclides in the soil. However, the roughness effect may be pronounced in cases where the radionuclide contamination is on or close to the surface (e.g., a recent spill). Two factors contribute to measurement variability in this situation. As with any *in situ* gamma ray measurement, the photons emitted from near the center of the detector field of view more heavily influence the measurement result than photons that originate from the outer edge of the field of view. Also, surface bumps closer to the center of the detector field of view will absorb or scatter some of the gamma rays originating further from the detector. These two factors in combination can produce highly variable measurement results when near-surface radionuclide distributions occur on an uneven ground surface. Calculations performed for this guidance document show that a crescent mound of soil 50 cm high and 1 m wide at a distance of 1 m from the detector changed the baseline result (no mound) by less than one percent.

4.11.6 Other Topographic Deviations

The discussion above indicates the robustness of the *in situ* technique especially when the radioactive contaminants are homogenously distributed and the soil surface is flat and level. (Note there is no difference between a sloped surface that is flat and a flat level surface.) However, the soil surface is not always flat, and the question arises as to the effect of topography on the measurements. Deviations from flat soil surfaces include cones, with the detector at the apex (the top of a hill or mound), and wells, with the detector at the bottom (pits with walls extending up to and even above the detector height). Non-flat terrain has two effects on *in situ* measurement results when comparing them to corresponding measurements performed on flat ground. Depending on how the terrain deviates from flat ground, some of the gamma emitting radionuclides may be closer to or farther from the detector. In addition, the fraction of the photons that are incident on the end face of the detector versus the fraction that strike the

detector side walls will be different from that which would occur for flat ground. For example, with the cone geometry, some of the gamma emitting nuclides are further away because the ground surface slopes away from the detector. Also a lower fraction of gamma photons will be incident on the end face of an HPGe detector because these photons must now travel through more soil to reach the detector end face due to the sloping surface. Overall, fewer photons will strike the detector when it is placed on a hill or mound. A well or pit may be thought of as a flat surface that has been folded upward to form the sides of the well or pit. In this geometry, especially in a pit with a small radius and high walls, a larger fraction of the photons will be incident on the sidewall of the detector and the gamma emitting radionuclides in the soil that forms the walls of the pit will be closer to the detector than would be the case for flat ground. Therefore, corrections may be necessary for source geometries that are very different from flat ground. In the following discussion, the contaminant distribution is assumed to be homogenous and the only variation is in the geometry of the soil surface.

The cone geometry represents a case where there is less fluence rate than from flat ground because the sloping ground surface is further from the detector than flat ground would be. Results will be biased low if the standard calibration factors are used. Figures 4-10 to 4-12 illustrate a number of cones of different size and shape and summarize the effect on gamma ray fluence for the 1,000 keV photon. The charted results are relative to the fluence rate observed for flat ground. In all cases, the differences are a few percent or less. For the extreme case where the diameter of the base of the cone approaches zero, the result of positioning a detector at the apex is equivalent to performing the measurement at a greater height above the ground.

The well geometry represents a ground half space that has had its outer regions folded up into walls. In this situation some of the source material is brought closer to the detector. The results of a measurement would be biased high as more gamma photons would reach the detector for a given radionuclide activity in the soil. Figures 4-13 and 4-14 show calculations for the increase in photon fluence as a function of parameters associated with the well geometry. When the height of the pit wall does not exceed the height of the detector (Figure 4-13), there is a 5 percent increase in the photon fluence when the detector is 1 m from the wall. This decreases to 2 percent as the detector is moved 10 m away from the wall. As the wall extends above the height of the detector (Figure 4-14), the detector becomes surrounded by the source and the photon fluence rate can double, relative to that of the flat ground geometry.

The most common geometries that arise from soil excavation activities are deep excavations with 2:1 slopes and trenches from the removal of utilities. Both of these geometries are a variation of the well

geometry, and a simple computer program has been written to calculate the activity correction factor for specific dimensions appropriate to any given measurement situation. Examples of the calculation and output files are provided in Section 5 of "Development and Deployment of the Excavation Monitoring System (EMS)" (DOE 2002a). It is anticipated that the EMS, with either an HPGe or NaI detector, will be the system most frequently deployed for *in situ* measurements in areas where there are pits, trenches or other rough terrain. By being able to reach into such areas from the outer boundary, the EMS provides benefits, in terms of reduced risk to personnel and reduced radiation exposure, that the other real time systems cannot match.

4.11.7 Guidance

- Soil conditions should be optimized (removing as much rubble as possible, mowing grass, etc.) prior to performing *in situ* gamma spectrometry to avoid the need to apply correction factors to the measurement results. Additionally, *in situ* measurements should be delayed until snow and standing water have infiltrated and evaporated so that the soil moisture content is within the acceptable range.
- If it is impractical to remove all obstructions from a measurement area, document the size and position of any remaining obstacles in relation to each location where *in situ* measurements are performed so that measurement results may be corrected for the presence of the obstructions.
- Calculate obstruction correction factors in accordance with the guidance provided in Section 4.11.2 of this manual. Either graphical or equivalent calculational techniques may be used to estimate obstruction correction factors. *In situ* measurement results will NOT be corrected for the presence of obstructions unless the estimated gamma flux deficit is equal to or greater than ten percent
- If *in situ* measurement results have been corrected to properly account for obstructions in the field of view, this must be documented in RTIMP records and in the Sitewide Environmental Database (SED).
- In view of the previous bullet, it is particularly important to remove rubble from the central portion of the detector field of view, because a unit area near the center of the field of view contributes proportionately more to the fluence at the detector than does a unit area on the outer edge of the field of view. If possible, choose an HPGe measurement location that is rubble free out to a radius of 3 meters for a 100-cm detector height or 1.25 meters for a 31-cm detector height. This will ensure that at least 70% of the total gamma flux will reach the detector unattenuated by rubble. Outside these radii, rubble will still absorb photons, but it will require a larger surface area covered with rubble to bring about a ten percent reduction in the incident photon flux.
- When it is not practical to remove all rubble from the detector field of view, the attenuating effect of the rubble can be reduced by judiciously choosing the measurement location and/or by reducing the detector height to ensure that any remaining rubble is near the periphery of the field of view.

- Ideally, HPGe measurements should be performed with the cylindrical axis of the detector perpendicular to the measurement surface. The maximum permissible angle between the detector axis and a perpendicular to the measurement surface is 20 degrees. Angles greater than 20 degrees can introduce measurement errors on the order of 5 to 10 percent.
- There is no need to apply geometry correction factors to measurement situations involving a trench or a single vertical soil wall as long as the HPGe detector height is greater than the height of the vertical wall. This is true even when the detector is very near the vertical wall.
- Do not perform HPGe measurements in grass which is taller than 3.5 feet (approximately waist high) as this could cause a low bias in measurement results of approximately 5 percent. Whenever possible, cut the grass to below eighteen inches (approximately knee height) before performing the measurements.
- When planning for *in situ* measurements in unusual topographic situations or geometries, consult with RTIMP personnel. Unusual topography may include the following: pits, trenches, steep slopes, measurements next to buildings, foundations, or excavation sidewalls, measurements in rocky soil or gravel, and measurements in wooded terrain.

4.11.8 See Also

4.5 Detector Field of View and Area Coverage
4.6 HPGe Grid Configurations
5.7 Data Review and Validation

4.12 ENVIRONMENTAL INFLUENCES ON IN SITU GAMMA SPECTROMETRY DATA

Environmental conditions change on a daily basis, and this leads to variation in the results of *in situ* gamma spectrometry measurements made with the HPGe and NaI systems. Environmental conditions are defined as weather-related phenomena such as soil moisture, rainfall, atmospheric temperature, and humidity. The initial evaluation of environmental conditions was done in 1997. The results and observations are reported in "Effect of Environmental Variables Upon *In Situ* Gamma Spectrometry Data" (DOE 1997, Addendum 3). The most important observations from that report with respect to operation of the HPGe and NaI systems are summarized below:

1. Soil moisture has a significant effect on HPGe and NaI measurements, as the water dilutes the reported result relative to dry-weight analyses performed in the laboratory. All HPGe and NaI measurements are corrected for soil moisture and results are reported on a dry-weight basis. Water in the soil also attenuates gamma photons, but this effect is minor [gamma photons are attenuated approximately 1 percent for every 10 percent of soil moisture] relative to the mass correction noted above.
2. Temperature has a minor effect upon *in situ* measurements over the range of 20° to 90° F. An indirect effect of higher temperature may be a steep moisture gradient in the top 10 to 15 cm of soil.
3. Humidity has no observable effect upon HPGe and NaI measurements.

4. Weather conditions, and the time of day that measurements are performed, have a significant effect upon HPGe and NaI measurements of Ra-226 activity. Gamma photons emitted by Rn-222 daughters are used to calculate Ra-226 activity, and weather conditions and temperature affect the buildup and dissipation of radon in surface soil. As radon levels fluctuate, the measured Ra-226 activity will vary. The average Ra-226 activity measurement is 30 percent higher in the morning, than in the afternoon; see Section 5.6.
5. Control charts were established for total uranium and Th-232, based upon the standard deviation of all measurements made from April 8, 1997 to October 14, 1997. Excellent long-term precision was observed for these two analytes. Although field quality control station (FQCS) results are no longer trended on control charts, the standard deviations of the measurement populations averaged 5 percent of the population means.
6. Control charts were established for Ra-226, based upon the standard deviation associated with all afternoon measurements over the same time period noted for uranium and thorium. Although field quality control station (FQCS) results are no longer trended on control charts, the standard deviation of the measurement population averaged 8 percent of the population mean.

4.12.1 Guidance

- Always convert wet-weight *in situ* measurement results to dry-weight equivalents to minimize bias associated with soil moisture. Comparison of *in situ* results to FRLs, hot spot criteria, or WAC should always be made on a dry weight basis.
- Do not take measurements unless the soil moisture is less than or equal to 40 percent. Measurements should not be taken on a muddy surface or if standing water is present within the field of view, as discussed in Section 4.4 and 4.11.
- Temperature effects will probably result in less than a 5 percent change in the value of any given measurement result, and measurements may be performed throughout the day without concern for temperature variations.
- Humidity does not effect HPGe and NaI measurements.
- An HPGe detector must be set up as a radon monitor to enable compensation for diurnal variations in the atmospheric concentration of radon when Ra-226 hot spots are being evaluated.
- Heavy dew, fog, or temperature inversions are likely to lead to the buildup of radon in soil or the atmospheric layer just above the ground. These conditions may bias morning measurements of Ra-226 activity to higher values, relative to afternoon measurements. When practical, perform Ra-226 measurement after 11:00 a.m.

4.12.2 See Also

4.4 Field Moisture Measurements
5.5 Moisture Corrected Data
5.6 Radium-226 Corrections
5.9 Quality Control Considerations for Field Measurements

4.13 SHINE AND BURIED SOURCES

Shine refers to radiation from a source that is outside the expected field of view of the HPGe and NaI detectors that is nevertheless detected. For example, gamma photon peaks in an *in situ* spectrum collected over soil may exhibit an artificially higher count rate because of gamma photons coming from radioactive material stored in a nearby building. Another form of shine can occur where the continuum, or background, under the peak is elevated because scattered radiation impinges on the detector; however, the gamma photon peaks are relatively unaffected because there is no direct line of sight to the shine source. This will cause the measurement uncertainty to be higher than normal, and may obscure small peaks.

The first form of shine mentioned above may contribute to the gamma spectral peaks for U-238, Th-232, and/or Ra-226, depending upon the radionuclide composition of the shine source. Figure 4-15 shows the historical locations for possible sources of shine formerly at the FCP, and Table 4-13 names the sources. Since the initial documentation of these sources of shine the source materials at all locations except 18 and 19 (Silos 1 and 2) have been removed, and the remediated sources are no longer considered potential sources of shine. As the remediation of the Fernald site approaches completion, shine from the Silos will also be eliminated. However, it is possible that new sources of shine will be temporarily created as a result of waste retrieval, processing, storage, and shipping activities associated with the ongoing remediation of the K-65 Silos.

A buried source, in the context of an *in situ* gamma spectroscopy measurement, refers to any unknown radioactive material in the top 20 cm of soil that lies beneath a layer of less radioactive or background soil. Sources that are buried deeper than 15 cm are not easily detected by the HPGe and NaI systems, due to severe attenuation by the overlying soil. At a soil depth of 5 cm, the 63.2 keV photons from Th-234 (U-238 daughter), are attenuated approximately 85 percent, while the 1001 keV photon from Pa-234m (Th-234 daughter) is attenuated about 40 percent. At 10 cm, the 63.2 and 1001 keV photons are attenuated approximately 100 and 60 percent, respectively. Because of the more severe attenuation of low energy photons, buried sources have a gamma signature that is reduced in lower energy photons and this signature may be difficult to distinguish from shine.

Three concerns are associated with shine and buried sources: 1) recognition of shine or the effects of a buried source; 2) distinguishing shine from radiation emanating from buried radioactive sources, and 3) correcting NaI and HPGe measurements for the effects of shine or buried sources. Two key factors aid in the resolution of these concerns: 1) radiation associated with shine or a buried source decreases as the distance from the source increases; and 2) the radiation is predominantly in the form of high energy gamma photons, as low energy photons from either source are almost completely attenuated.

Figures 4-16 and 4-17 present HPGe data taken to assess the effect of shine on *in situ* gamma spectrometry measurements at one particular location at the FCP. This case study involved measurements taken at former Soil Stockpile 5 (SP-5), and forms the basis for the guidance provided below. Total uranium measurements are used in the examples discussed in this section; however, the principles involved and the guidance also apply to thorium and radium.

Figure 4-16 shows total uranium concentrations (calculated using the weighted average of gamma photons in Table 2-3) on and in proximity to SP-5. The solid circles represent measurements (1.0 meter HPGe detector height, 5 minute count time) taken to ascertain the magnitude of shine coming from nearby T-hoppers. Open circles represent HPGe measurements taken on the north side of SP-5. Measured total uranium concentrations decrease significantly from a high of 940 mg/kg adjacent to the T-hoppers to concentrations consistently less than the uranium FRL (82 mg/kg) at locations well removed from the T-hoppers. (The grey area located east of the center in Figures 4-16 and 4-17 represents rubble zones.)

Figure 4-17 shows the ratio of total uranium calculated from low energy gamma photons (weighted average of 63.2 and 92.6 keV) to total uranium calculated from a high-energy gamma photon (1001 keV). These ratios change from lows of approximately 0.02 adjacent to the T-hoppers to high values approaching 0.9 at the northwest corner of SP-5. The significance of these ratios is that measurements comprised mostly of shine, or radiation coming from deeply buried sources, will have very low ratios due to the attenuation of the low energy gamma photons. Conversely, measurements in which gamma photons originate within the top few cm of soil will have ratios near unity, based on field experience at the FCP. Note that the ratios can only be calculated with HPGe data sets, as uranium results for the NaI measurements are based solely on the 1001 keV photon.

Prior to performing HPGe measurements, hand held meters (dose rate meters and/or friskers) are used to check the ambient background in the vicinity of the measurement location. This can alert the technician to the possible presence of sources of shine. An abnormally high background reading could be indicative of the presence of shine. However, background measurements are generally not useful indicators of the presence of deeply buried sources. Low-energy to high-energy photon activity ratios, like those in Figure 4-17, are calculated for each of the primary isotopes of concern for all HPGe measurements to determine if shine or buried sources may be interfering with the results. If the total uranium calculated from an error weighted average of the 63.2 keV and the 92.6 keV photopeaks is less than 80 percent of

the concentration calculated using the 1001 keV peak, the uranium result will be flagged with an "S" (Sections 5.7.1 and 5.7.2) to designate that the measurement result is suspect. Ra-226 and Th-232 results will be evaluated in like manner to determine if the measured activities of these isotopes may have been affected by shine or buried sources. That is the error weighted mean activity from the two low-energy photopeaks used to quantify the isotope in question (Table 2-3) will be compared to the activity computed from the high-energy peak. Despite the fact that the attenuation differences between low-energy and high-energy photopeaks for Ra-226 and Th-232 will be smaller than for the case of U-238, for programmatic consistency, the 80% criterion will also be used to flag Ra-226 and Th-232 results that are "suspect" because of possible interference from shine or buried sources.

4.13.1 Guidance

- Using the map of potential shine sources (Figure 4.15) as a guide, also factoring in the current status of ongoing demolition projects, determine if the area to be measured is likely to be affected by shine.
- When measuring an area believed to be susceptible to shine, HPGe measurements shall be made adjacent to the potential shine source and at regular intervals between the potential shine source and the area to be measured. Such measurements may verify the existence of shine (decreasing detector response with increasing distance from source) and serve as the basis for interpreting *in situ* measurement results.
- NaI or HPGe measurements in an area influenced by shine will be accepted as valid if they do not exceed a trigger level or regulatory limit, regardless of the contribution of shine. If the low-energy photon to high energy photon ratio calculated for uranium from the HPGe data is less than 0.8 (80 percent), the measurement is flagged with an "S" and the ambient background radiation level is measured with a handheld meter to determine if the data will be flagged as influenced by shine or a buried source.
- Examine available process knowledge to identify possible sources of shine. Look for discolored areas, debris, or signs that soil has been disturbed. Use a hand-held survey instrument to determine the direction from which shine may be impinging upon the measurement area. Also, evaluate the relative size of and distance to potential shine sources and use shielding and distance rules to interpret readings.
- In extreme situations, the amount of low-energy versus high-energy scatter in spectra can be used to indicate when extraneous sources of radiation are present. Low-energy scatter is reduced for buried sources, relative to shine sources.

4.13.2 See Also

5.7 Data Review and Validation

4.14 INTERPRETATION OF NaI TOTAL-ACTIVITY DATA

Total activity (or gross counts) is obtained by summing all of the counts in the NaI gamma spectrum. Much of the following discussion was developed for the RTRAK system, but it applies to other NaI systems as well. Based upon data presented in the January 1999 RTRAK Applicability Study (DOE 1999b), the following conclusions concerning total activity data were drawn.

- Total activity measurements exhibit a high degree of precision. That is the counting uncertainty is relatively low.
- Total activity measurements can be effective in defining general patterns of elevated activity.
- Total activity measurements do not provide radionuclide-specific information.

When compared to U-238 and its progeny, both the abundance and relatively high energy of gamma photons associated with Th-232 and Ra-226 progeny result in higher recorded values for total activity. A doubling of the Th-232 or Ra-226 activity above background levels will produce a noticeable change in the measured total activity, whereas an equivalent increase in the U-238 activity would produce no measurable effect. The U-238 activity must be on the order of tens of pCi/g or greater before measurable changes in total activity are easily observed.

A comparison of the Uranium Soil Integrated Demonstration (USID) and South Field data (Table 4-14) illustrates these observations. The U-238 activity in the South Field is approximately one-half that observed in the USID area, yet total activity in the South Field is about 17 percent higher than the USID area. Higher total activity in the South Field is due to higher Ra-226 activity.

While, elevated total activity at the FCP can be generally attributed to the presence of all the radionuclides of concern, the development of a correlation between total activity and U-238 is particularly useful for screening for above-WAC levels of U-238. As illustrated in Figure 4-18, a linear regression of RTRAK total activity measurements versus U-238 activity measured in the drum baling area (an area of high activity for U-238) has an upper 95 percent confidence interval of 18,000 cps corresponding to a U-238 activity at the WAC level. This total activity level constitutes a rough correspondence with above-WAC levels of U-238, which would trigger additional measurements with HPGe instruments.

4.14.1 Guidance

- Total activity less than 3000 cps suggests that U-238, Th-232 and Ra-226 are below their FRLs. This guidance is for a U-238 FRL of 27 pCi/g; it does not hold for U-238 FRLs of 3.3 or 6.7 pCi/g.
- Total activity between 5,000 and 15,000 cps suggests a potential hot spot for U-238, Th-232 or Ra-226.
- Total activity above 18,000 cps may indicate a WAC exceedance. Areas with total activity in excess of 18,000 cps should be further characterized with HPGe measurements.
- Total activity data are primarily used by field personnel to guide additional HPGe measurements.

4.14.2 See Also

2.0 *In Situ* Gamma Systems Operated at the FCP
4.8 Trigger Levels
4.9 Detection of Above-WAC Uranium Contamination
4.13 Shine and Buried Sources

4.15 MAPPING CONVENTIONS

Maps that display real-time *in situ* gamma spectroscopy data are crucial for proper analysis and decision-making. This section discusses mapping protocols, including minimum mapping requirements to support various remedial decisions, and the standard color formatting of maps produced for NaI and HPGe measurements.

4.15.1 Mapping Formats

Maps are produced for U-238 (or total uranium), Th-232, Ra-226 and gross activity (NaI only). Area coverage is illustrated using color-coded squares and circles for NaI and HPGe measurements, respectively. The data markers plotted on the maps are color coded to represent specified radionuclide concentration ranges to facilitate identification of measurements that exceed regulatory limits. Green is used to identify measurement results that are below hot spot action levels, i.e., less than three times the FRL for U-238 (27 pCi/g FRL only), Th-232 and Ra-226 . This convention applies to both NaI and HPGe data. Black is used on uranium maps to denote activity levels that fall between the hot spot action level and the WAC trigger level. As there is no WAC trigger level for Th-232 or Ra-226, black data markers are not present on thorium and radium maps. Red is used to indicate measurement results that exceed the WAC trigger for uranium or three times the FRL for Th-232 and Ra-226. NaI maps based on gross activity use green to indicate less than 3,000 counts, black for 3,000 to 5,000 counts, blue for 5,000 to 15,000 counts, red for 15,000 to 18,000 counts and solid red for over 18,000 counts. In general, the

highest measurement is indicated on each map along with the legend, title, measurement date, project number, and list of data support files. Figures-4-19 through 4-22 are examples of NaI and HPGe maps.

4.15.2 Mapping Van and Real-Time Maps

Real-time mapping of NaI and HPGe data may be accomplished using a mapping van that has been equipped with a computer, printer and wireless communication hardware. The mapping van receives spectral data from the various gamma detection systems in real time (i.e., immediately after the raw spectra are processed by the NaI and HPGe systems). Spectra and associated data from the NaI and HPGe systems are continuously monitored to assess surface coverage and to evaluate the quality of the data while a survey is in progress. QC checks on the data are performed using data validation checklists prior to preparing maps of U-238 (or total uranium), Th-232, and Ra-226 activities. The maps are used by Characterization, Construction and Waste Management personnel to support remedial decisions on soil excavation and pre-certification. Data are archived at the end of a shift by transferring data from mapping van computers into the real-time directory of the FCP computer network.

4.15.3 Guidance

- On maps displaying Ra-226 data, the Ra-226 values will be corrected as described in Section 5.6 when a trigger level for Ra-226 has been exceeded.
- The mapping van may be employed when making NaI and/or HPGe measurements for excavation control; however, it is typically not used for making precertification measurements.
- The advantage of using the mapping van for excavation control surveys is that maps can usually be produced within 30 to 45 minutes after completing *in situ* measurements. Characterization leads may monitor the real time mapping process so that they can request additional measurements if they deem area coverage to be less than adequate.
- Mapping for precertification purposes is usually done after completing all *in situ* measurements in a given area because additional excavation would typically be required only in small, isolated areas that are best addressed after a review of an entire area survey.

4.15.4 See Also

3.1.2 Estimation of Above-FRL Excavation Boundary
3.1.3 Above-WAC Detection, Confirmation and Delineation
3.3.1 Hot Spot Evaluation
4.5 Detector Field of View and Area Coverage
4.14 Interpretation of NaI Total Activity Data
5.6 Radium-226 Corrections

TABLE 4-1
FIELD OF VIEW FOR STANDARD HPGe DETECTOR HEIGHTS

Detector Height (cm)	Radius of Field of View (m)	Area of Field of View (m^2)
100	6.0	113
31	2.5	19.6
15	1.0	3.1

TABLE 4-2
NaI MEASUREMENT AREA* AS A FUNCTION OF SPEED AND DATA ACQUISITION TIME

Speed (mph)	NaI Field of View (m^2)		
	2 Sec Count	4 Sec Count	8 Sec Count
0.5	18.7	20.7	24.8
1.0	20.7	24.8	33.1
1.5	22.8	29.0	41.3
2.0	24.8	33.1	49.5

* Values in the main body of the table show area in square meters for detector height of 31 cm.

TABLE 4-3
AREA COVERED FOR NaI STANDARD OPERATING CONDITIONS*

Number of Passes	Number of Measurements per NaI Platform Pass									
	1		2		4		10		100	
	Total Field of View (m^2)	Field of View per Measurement (m^2)	Total Field of View (m^2)	Field of View per Measurement (m^2)	Total Field of View (m^2)	Field of View per Measurement (m^2)	Total Field of View (m^2)	Field of View per Measurement (m^2)	Total Field of View (m^2)	Field of View per Measurement (m^2)
1	24.8	24.8	33.1	16.5	49.5	12.4	98.9	9.89	839	8.39
2	48.3	24.1	63.6	15.9	94.4	11.8	187	9.33	1571	7.85
4	95.1	23.8	125	15.6	184	11.5	362	9.06	3034	7.58
10	236	23.6	308	15.4	453	11.3	889	8.89	7423	7.42
100	2343	23.4	3059	15.3	4492	11.2	8790	8.79	73260	7.32

* Standard operating conditions include 1 mph operating speed, 4-second data acquisition time, and 0.6 m overlap between passes. At a height of 31 cm, the radius of the NaI detector field of view is 2.3 meters.

TABLE 4-4
AREA COVERED AS A FUNCTION OF OVERLAP WIDTH*

Parameter	0 Overlap Between Adjacent Passes	0.6 meter Overlap Between Adjacent Passes	1.0 meter Overlap Between Adjacent Passes
Number of Measurements per Pass	75	75	75
Number of Passes	30	30	30
Total Measurements	2250	2250	2250
Total Field of View (m^2)	19006	16662	15088
Average Field of View per Measurement (m^2)	8.45	7.41	6.71

*All results based on a scan speed of one mile per hour and a single spectrum acquisition time of four seconds. At a height of 31 cm, the radius of the NaI detector field of view is 2.3 meters.

TABLE 4-5
COMPARISON OF HPGe MEASUREMENT RESULTS FOR VARIOUS COUNT TIMES AND DETECTOR HEIGHTS

Detector Height (cm)	Count Time (sec.)	Statistical Parameters	Analytes			
			Total Uranium (mg/kg)	Thorium-232 (pCi/g)	Potassium-40 (pCi/g)	Radium-226 (pCi/g)
15	300	Number *	10	10	10	10
		Mean	71.2	0.89	10.3	0.98
		Std. Dev.	2.99	0.03	0.27	0.16
15	900	Number *	10	10	10	10
		Mean	71.3	0.86	10.3	0.98
		Std. Dev.	1.61	0.02	0.24	0.15
31	300	Number *	10	10	10	10
		Mean	70.2	0.87	10.3	1.04
		Std. Dev.	3.04	0.03	0.42	0.16
31	900	Number*	10	10	10	10
		Mean	69.5	0.85	10.3	1.01
		Std. Dev.	1.98	0.03	0.24	0.15
100	300	Number*	10	10	10	10
		Mean	66.8	0.83	10.0	1.01
		Std. Dev.	3.35	0.04	0.29	0.20
100	900	Number *	10	10	10	10
		Mean	65.9	0.83	10.1	0.99
		Std. Dev.	2.35	0.02	0.18	0.18

*Number of measurements

TABLE 4-6
HPGe TRIGGER LEVEL FOR WAC EXCEEDANCES

Radionuclide	Regulatory Application	Regulatory Limit	Trigger Level (5 min count time)
Total Uranium	WAC	1030	31-cm height: 928 mg/kg 100-cm height: 400 mg/kg

TABLE 4-7
MOST RECENTLY DETERMINED NaI TRIGGER LEVELS FOR URANIUM WAC EXCEEDANCE

Platform	Regulatory Limit	Trigger Level (4 sec count time)
RTRAK	1030 mg/kg	883 mg/kg
RSS1	1030 mg/kg	915 mg/kg
RSS2	1030 mg/kg	896 mg/kg
EMS	1030 mg/kg	891 mg/kg
Gator	1030 mg/kg	878 mg/kg
RSS3	1030 mg/kg	896 mg/kg

TABLE 4-8
URANIUM ACTION LEVELS FOR HPGe MEASUREMENTS WHEN WAC EXCEEDANCE AREAS ARE LESS THAN THE DETECTOR FIELD OF VIEW

HPGe Detector Height (cm)	WAC Exceedance Radius (m)	WAC Exceedance Area (m^2)	Total U Action Level (mg/kg)
31	0.5	0.8	400
	1.0	3.1	700
	1.5	7.1	880
100	1.0	3.1	280
	1.5	7.1	400
	2.0	12.6	500
	3.0	28.3	700
	4.0	50.3	800

TABLE 4-9
EFFECT OF GRASS ON *IN SITU* GAMMA SPECTROMETRY MEASUREMENTS

Analyte (Units)	Detector Height (cm)	Dry Weight Concentration in Soil with 41.5-inch Grass	Dry Weight Concentration in Soil with 3-inch Grass	% Decrease(-) or Increase(+) in Concentration
Total Uranium	100	67.0 ± 2.3**	70.8 ± 2.2	-5.37*
(mg/kg)	31	67.9 ± 2.3	72.0 ± 2.2	-5.69
Th-232	100	0.99 ± 0.03	1.17 ± 0.03	-15.4
(pCi/g)	31	1.13 ± 0.03	1.20 ± 0.03	-5.83
Potassium-40	100	13.8 ± 0.3	13.3 ± 0.2	+3.76
(pCi/g)	31	14.2 ± 0.3	14.1 ± 0.3	+0.71

* % Decrease or increase = [100*(41.5-inch concentration/3-inch concentration)-1]
** ± One standard deviation counting error
Average Difference in Concentration for 100 cm Detector Height = -5.67 percent
Average Difference in Concentration for 31 cm Detector Height = -3.60 percent

TABLE 4-10
EFFECT OF GRASS ON ATTENUATION OF GAMMA PHOTONS USED TO QUANTIFY URANIUM-238

Detector Ht. (cm)	Grass Ht. (in)	U-238 from 63.2 keV (pCi/g)	U-238 from 92.6 keV (pCi/g)	U-238 from 1001.1 keV (pCi/g)	Ratio of 63.2 to 1001.1 keV Concs.	Ratio 41.5" Grass Data to 3" Grass Data*	Ratio of 92.6 to 1001.1 keV Concs.	Ratio 41.5" Grass Data to 3" Grass Data**
100	41.5	16	15	14	1.14	0.87	1.07	1.01
100	3	21	17	16	1.31		1.06	
31	41.5	16	14	16	1.00	0.95	0.88	0.98
31	3	20	17	19	1.05		0.90	

* Ratio of 63.2 to 1001.1 keV concentrations for 41.5" grass divided by the corresponding result for 3" grass
** Ratio of 92.6 to 1001.1 keV concentrations for 41.5" grass divided by the corresponding result for 3" grass

TABLE 4-11
PARAMETERS RELATED TO ESTIMATION OF FLUENCE DEFICIT REPORTED IN TABLE 4-12

Object	Nature	Shape	Dimensions (m)	Closest Distance (m)
Excavation Wall	no source	Rectangular	30 x 50	3
Water Puddle	no source	Irregular	2 x 3.5	1.5
Tree	no source	Circle	1 (diameter)	2

TABLE 4-12
APPROXIMATE PERCENT DEFICIT OF FLUENCE RATE FOR OBJECTS IN TABLE 4-11

Object	Ring Number					Total
	6	7	8	9	>9	
Excavation Wall	0	0	2	3.5	4	9.5
Water Puddle	1	1.5	1	0	0	3.5
Tree	0	0.5	0.5	0.5	0.5	2
All Objects	1.0	2	3.5	4	4.5	15

TABLE 4-13
POTENTIAL SOURCES OF SHINE AT THE FCP (HISTORICAL AND CURRENT)

Source Index Number	Potential Source	Type of Shine	Remediation Status As of Dec. 2004
1	T-hopper at SP-5	Uranium	Remediation Complete
2	Quonset hut #3	Th-232	Remediation Complete
3	KC-2 Warehouse	Uranium	Remediation Complete
4	T-hoppers by Plant 5 Warehouse	Uranium	Remediation Complete
5A	Old Plant 5 Warehouse	Th-232	Remediation Complete
5B	Thorium Warehouse	Th-232	Remediation Complete
6	Tension Support Structure #6, Plant 1 Pad Area	Uranium	Remediation Complete
7	Tension Support Structure #5, Plant 1 Pad Area	Uranium	Remediation Complete
8	Tension Support Structure #4, Plant 1 Pad Area	Uranium	Remediation Complete
9	General In-Process Warehouse, Plant 1 Pad Area	Uranium	Remediation Complete
10	Chemical Warehouse	Uranium	Remediation Complete
11	Incinerator Building	Uranium	Remediation Complete
12	Hot Raffinate Building	Uranium	Remediation Complete
13	Plant 4 Warehouse	Uranium	Remediation Complete
14	Metals Production Plant	Uranium	Remediation Complete
15	Finished Products Warehouse	Uranium	Remediation Complete
16	Pilot Plant Warehouse	Uranium	Remediation Complete
17	Sewage Treatment Plant Incinerator	Uranium	Remediation Complete
18	K-65 Storage Tank (South)	Ra-226	Remediation Underway
19	K-65 Storage Tank (North)	Ra-226	Remediation Underway
20	Uranium Metal Storage Area	Uranium	Remediation Complete

TABLE 4.14
COMPARISON OF TOTAL ACTIVITY AND ISOTOPIC DATA COLLECTED WITH THE RTRAK*

Remediation Area	Uranium-238 (pCi/g)		Thorium-232 (pCi/g)		Radium-226 (pCi/g)		Gross Counts (cps)	
	Area Mean	Area Std. Dev.	Area Mean	Area Std. Dev.	Area Mean	Area Std. Dev.	Area Mean	Area Std. Dev.
USID	17.2	14.1	0.75	0.19	0.81	0.40	2456	176
South Field	9.71	14.3	0.83	0.22	1.38	0.47	2883	180
Drum Baling	209	69.8	3.83	0.78	8.46	2.44	15,703	2,298

* The RTRAK was operated at 0.5 mph with an 8-second data acquisition time

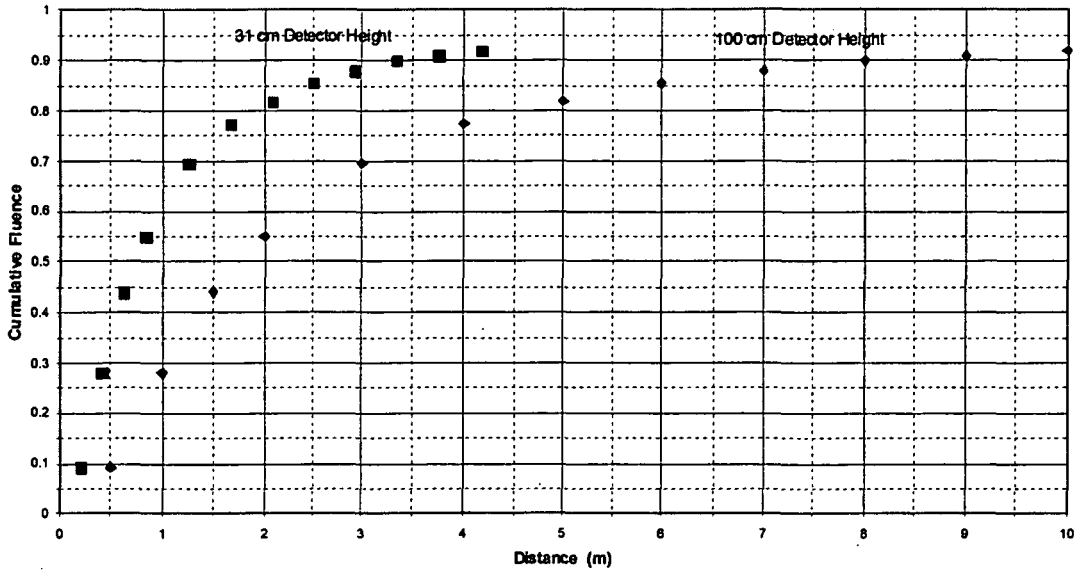


Figure 4-1. Cumulative Fluence of 1000 keV Photons for Detector Heights of 100 cm and 31 cm

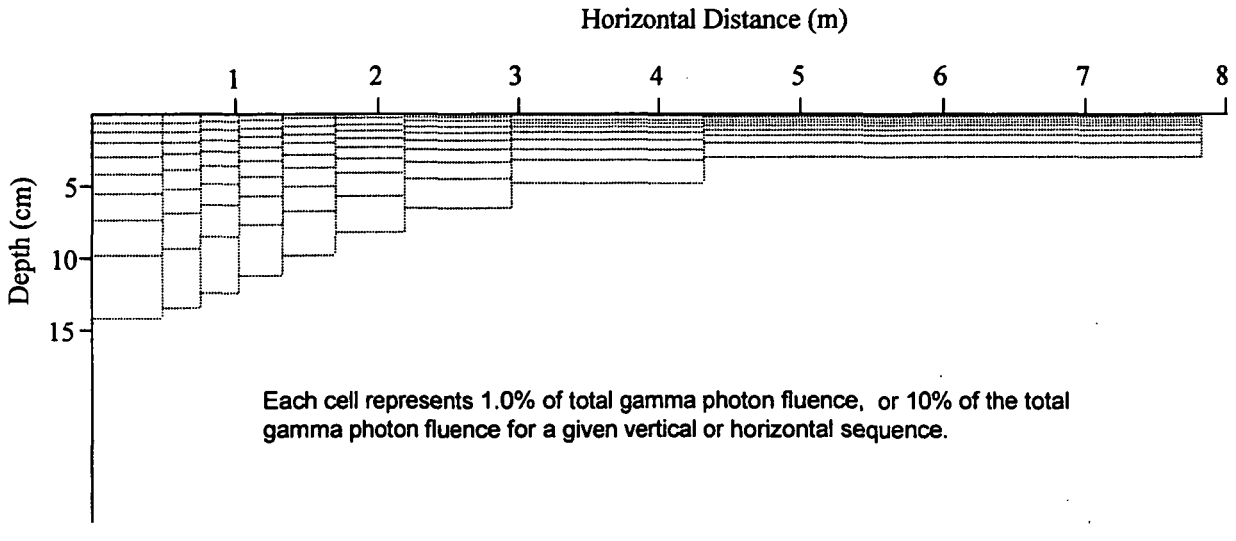


Figure 4-2. Fluence of 500 KeV Gamma Photons as a Function of Soil Depth and Horizontal Distance from the Detector at a 100 cm Height

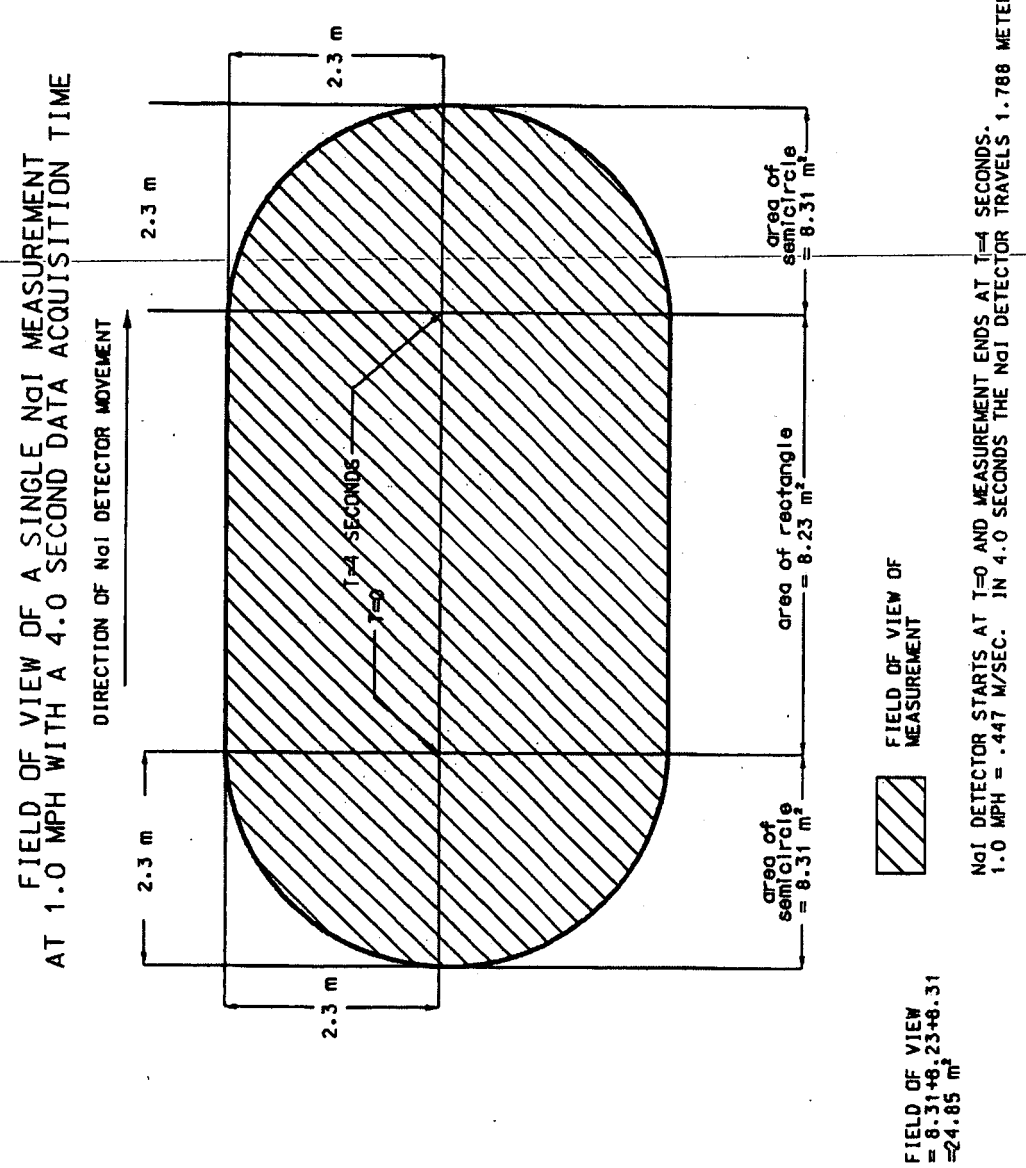


Figure 4-3. Area Covered by a Single NaI Measurement at 1.0 mph with a 4.0-Second Data Acquisition Time

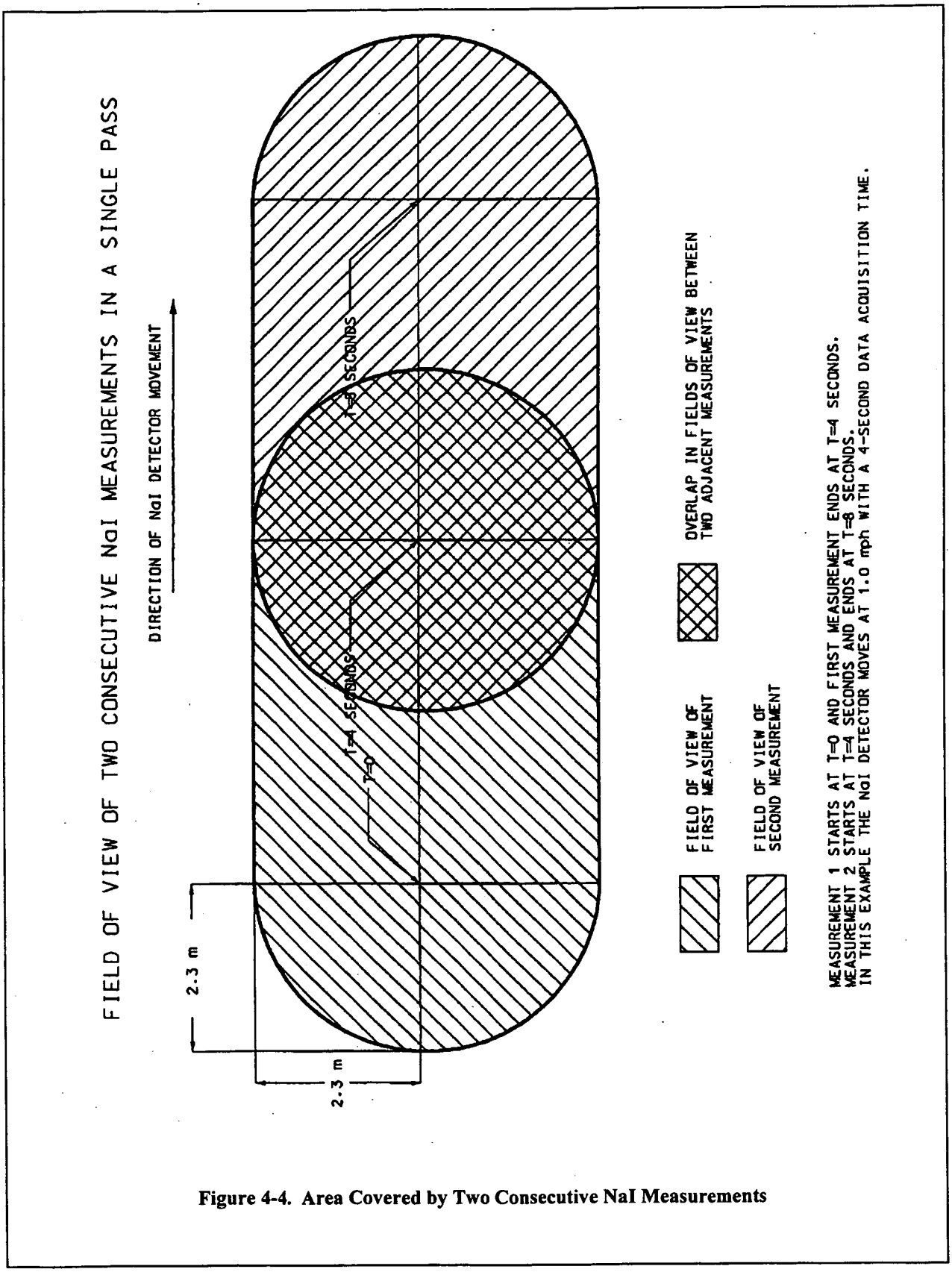


Figure 4-4. Area Covered by Two Consecutive NaI Measurements

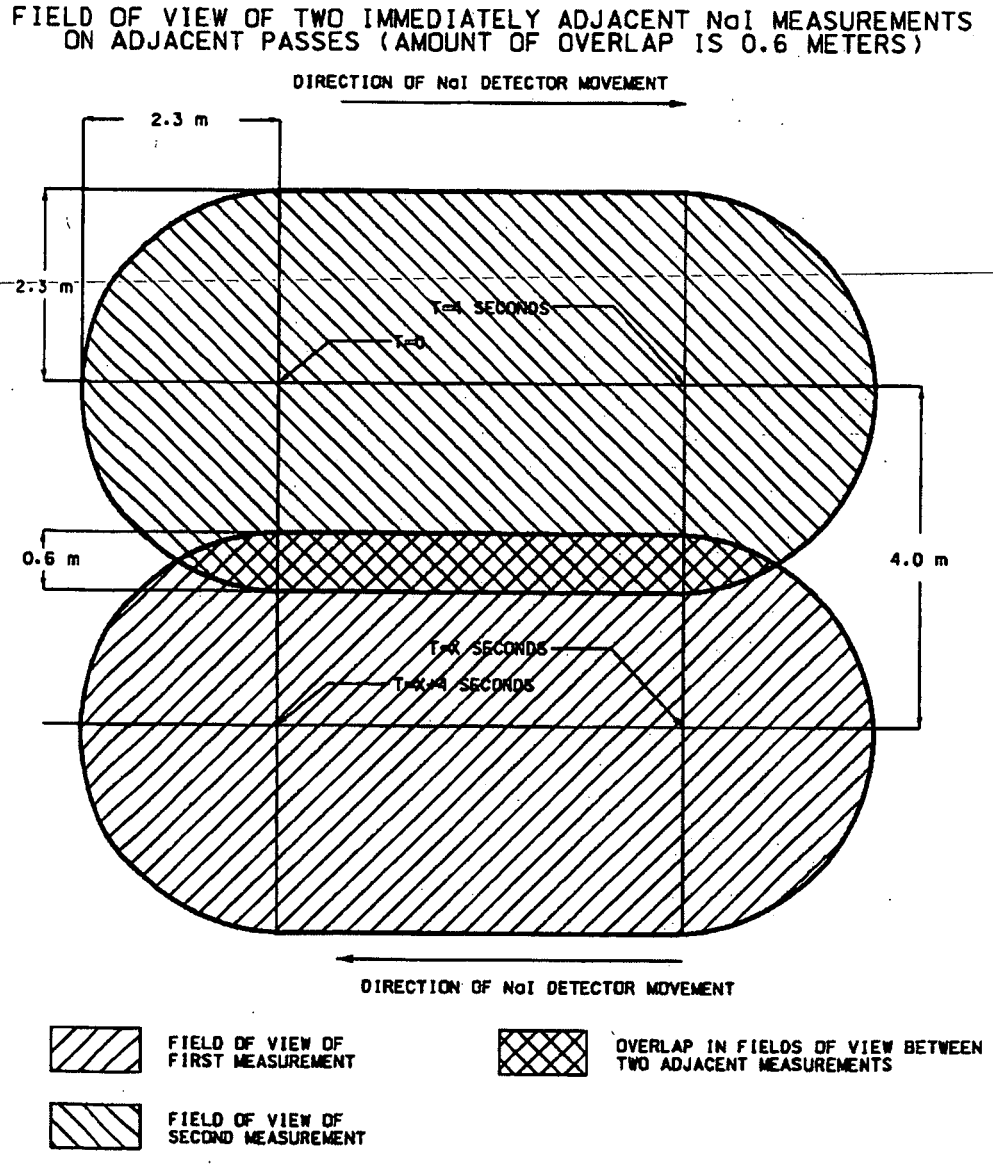


Figure 4-5. Area Covered by Two Adjacent NaI Traverses

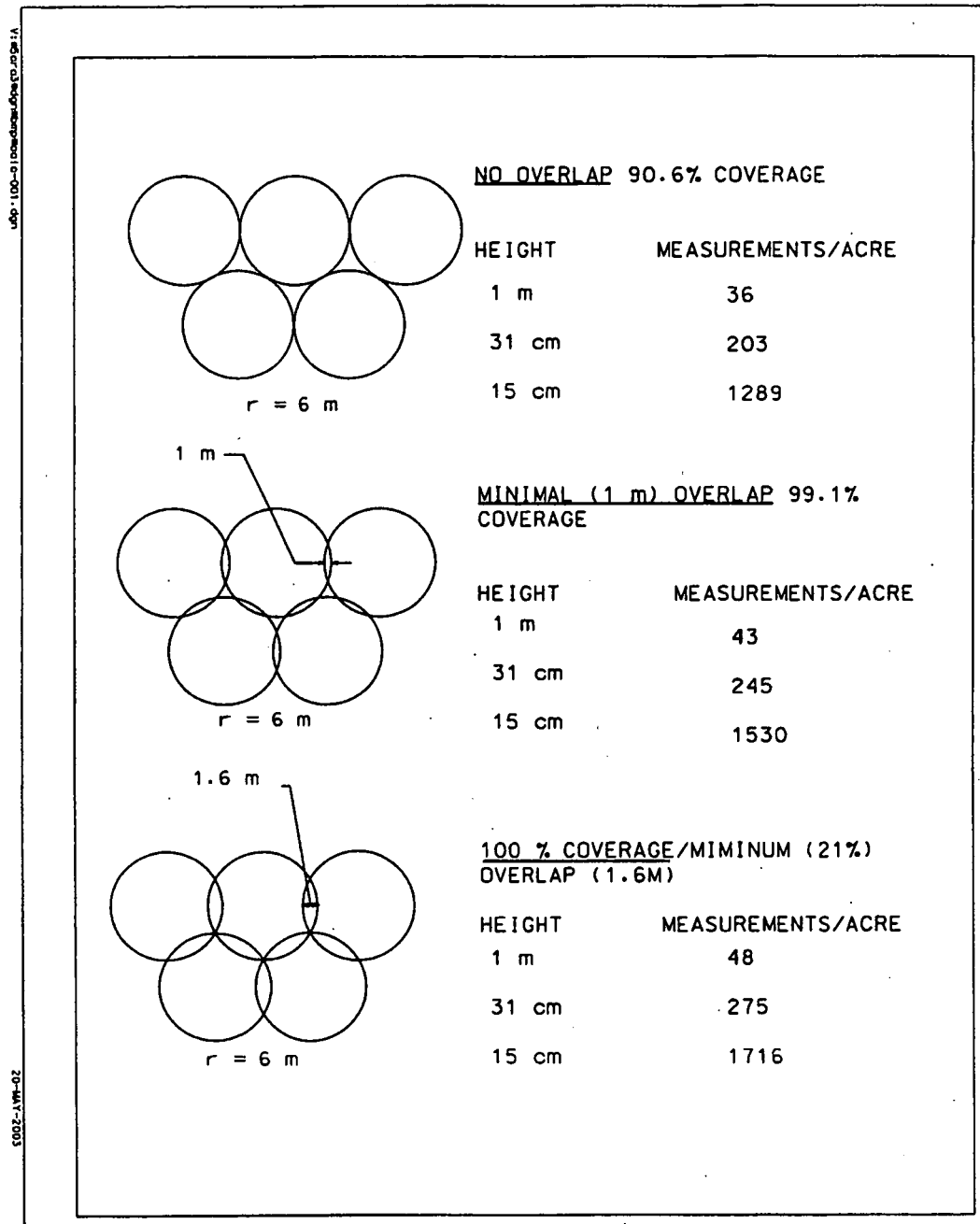


Figure 4-6. Grid Configurations for HPGe Measurements

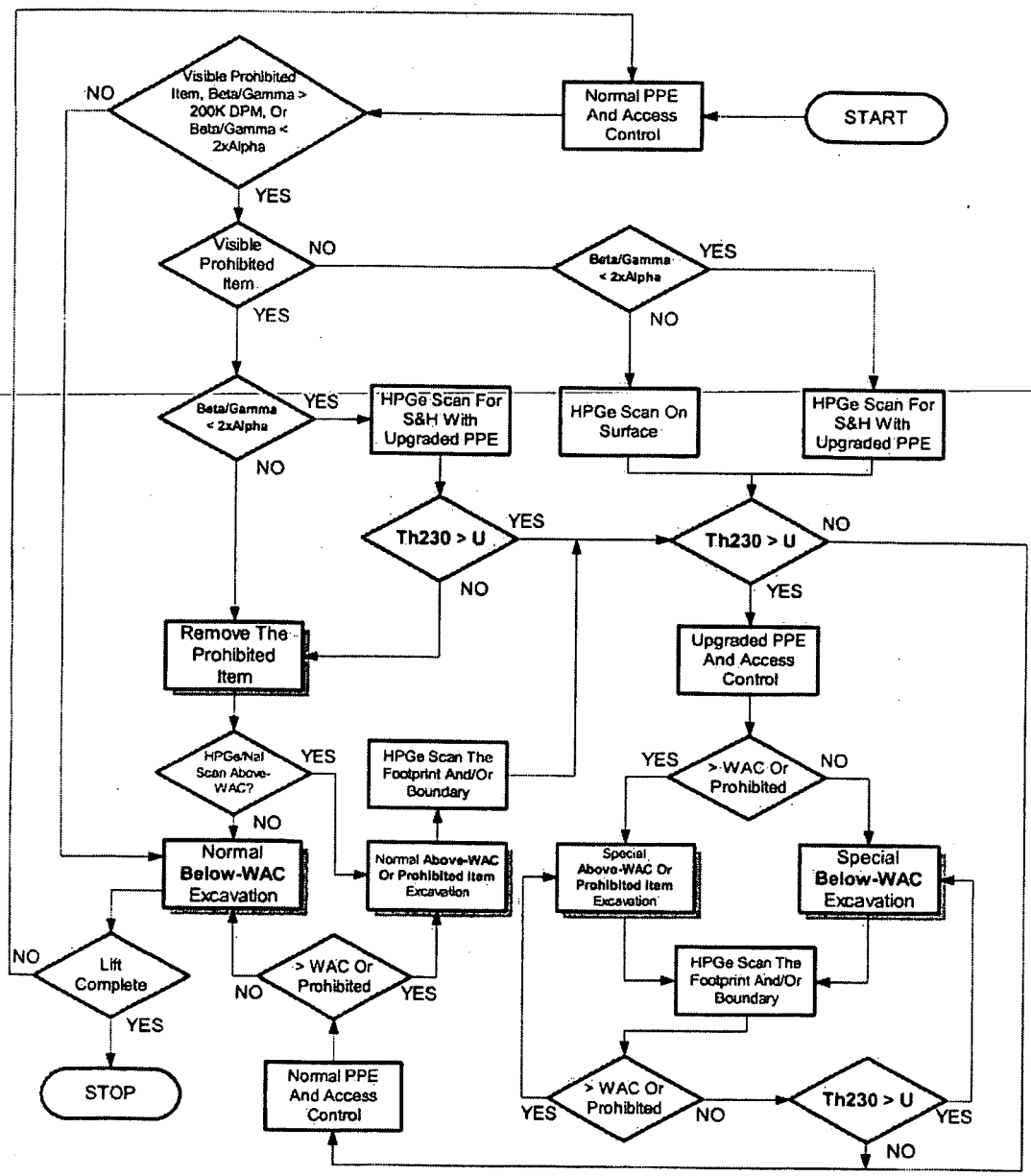


Figure 4-7. General Decision Making Process for Real-Time Scans between Excavation Lifts in Thorium-230 Areas

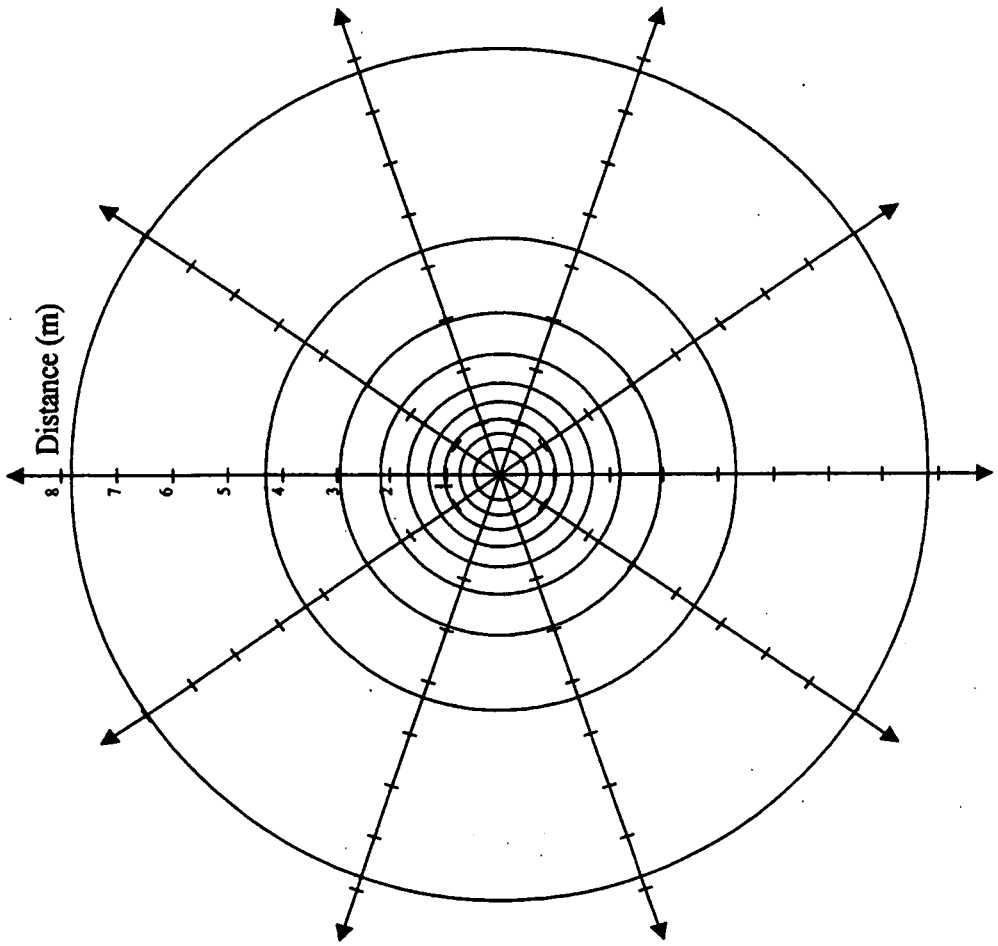


Figure 4-8. Fluence Yield from Ground Cells Below the Detector

Individual ground cells contribute one percent to the photon fluence measured by a detector at a height of 100 cm. Each ten-cell ring contributes 10% of the fluence measured by the detector. The region beyond the outermost ring also contributes 10%.

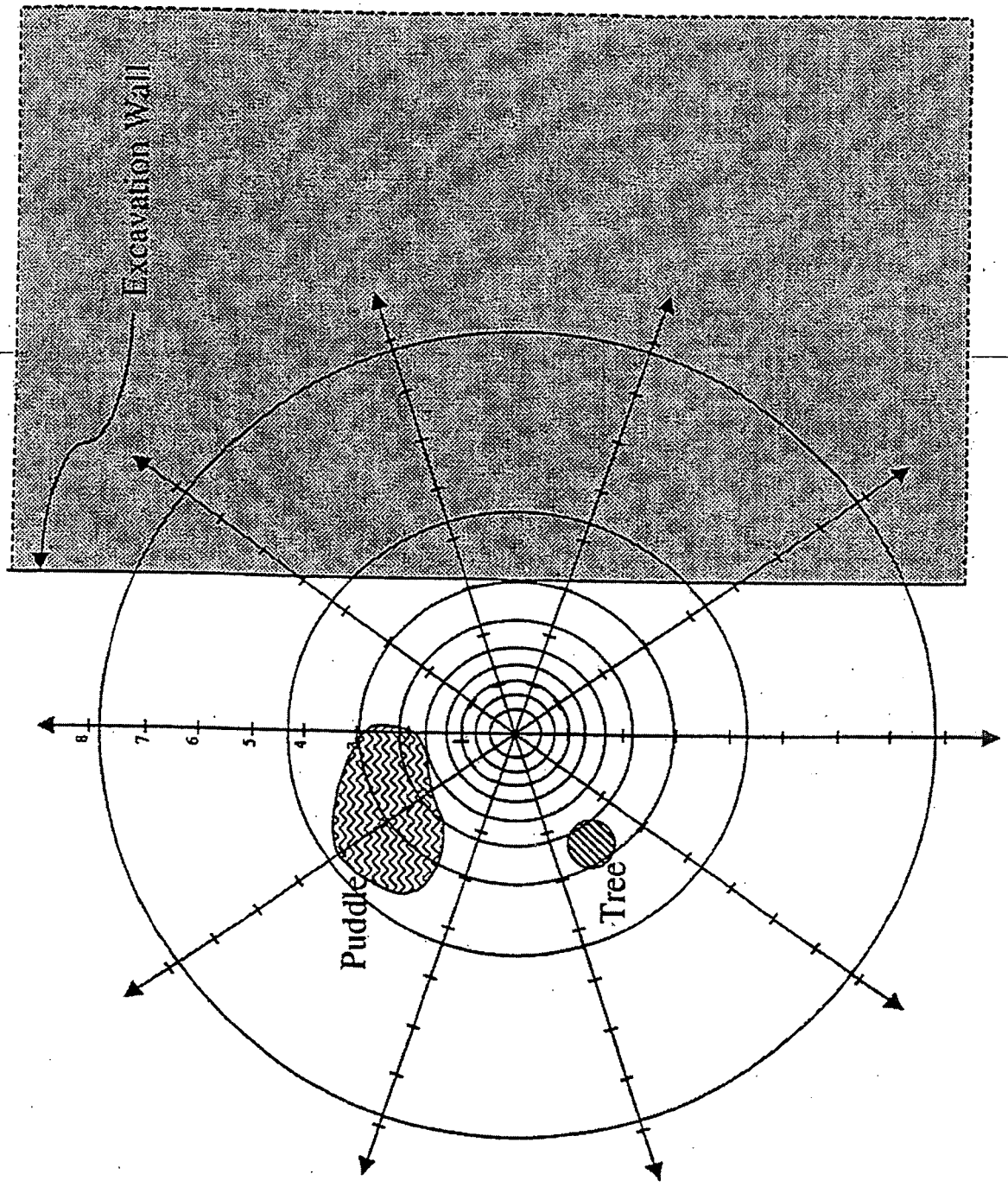


Figure 4-9. Example Measurement Location Diagram for Estimating Fluence Deficit

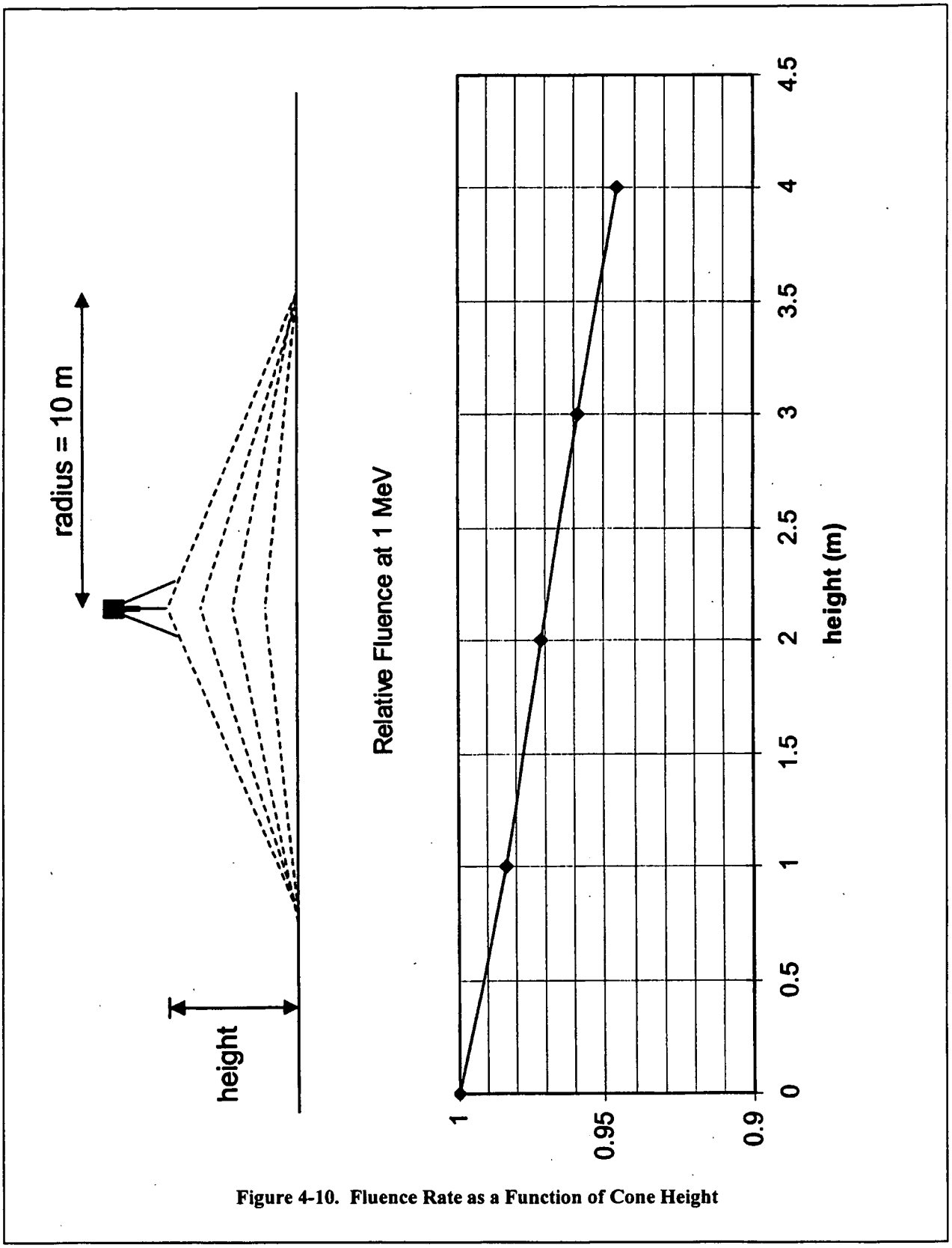


Figure 4-10. Fluence Rate as a Function of Cone Height

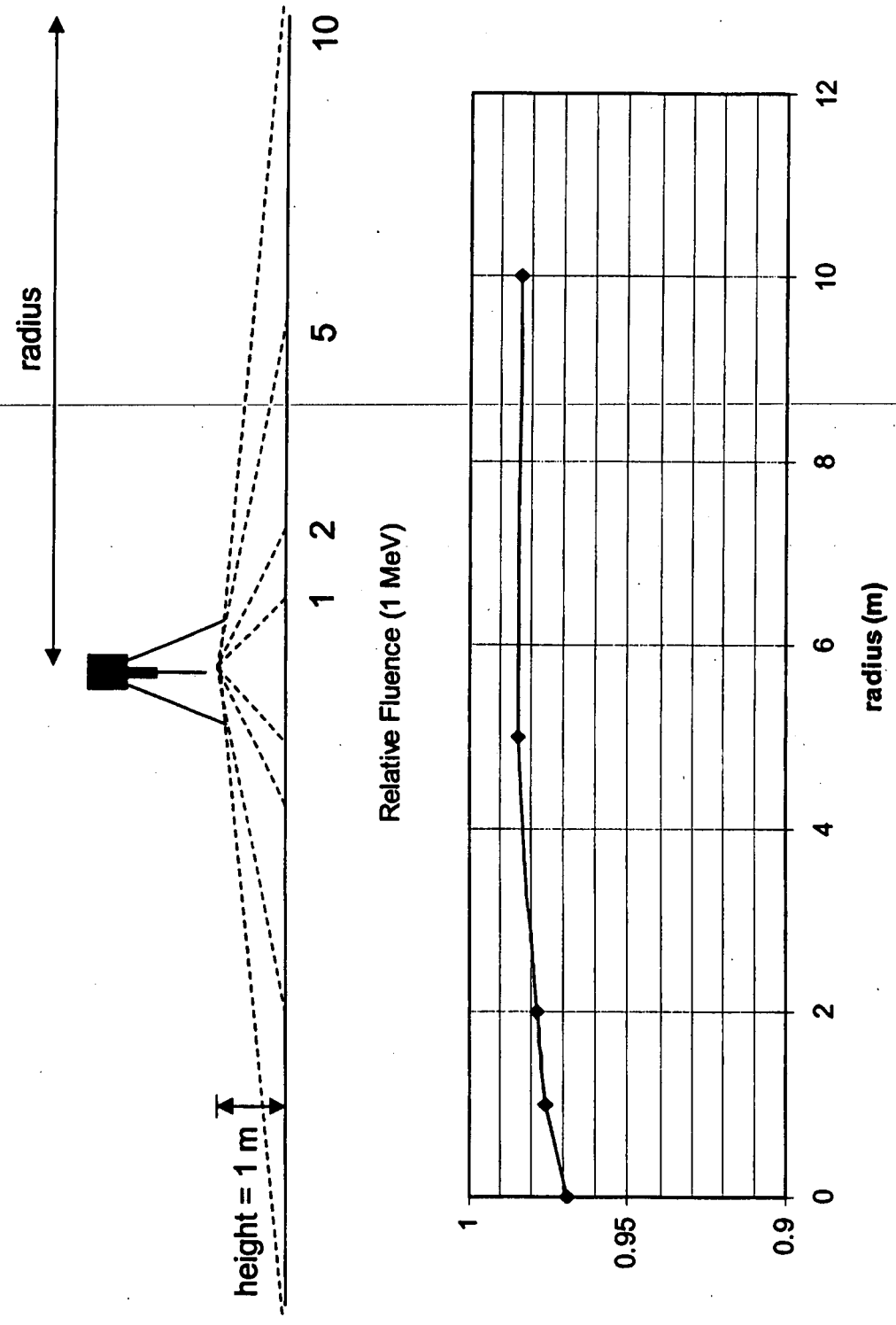


Figure 4-11. Fluence Rate as a Function of Cone Radius for a Cone Height of 1 m

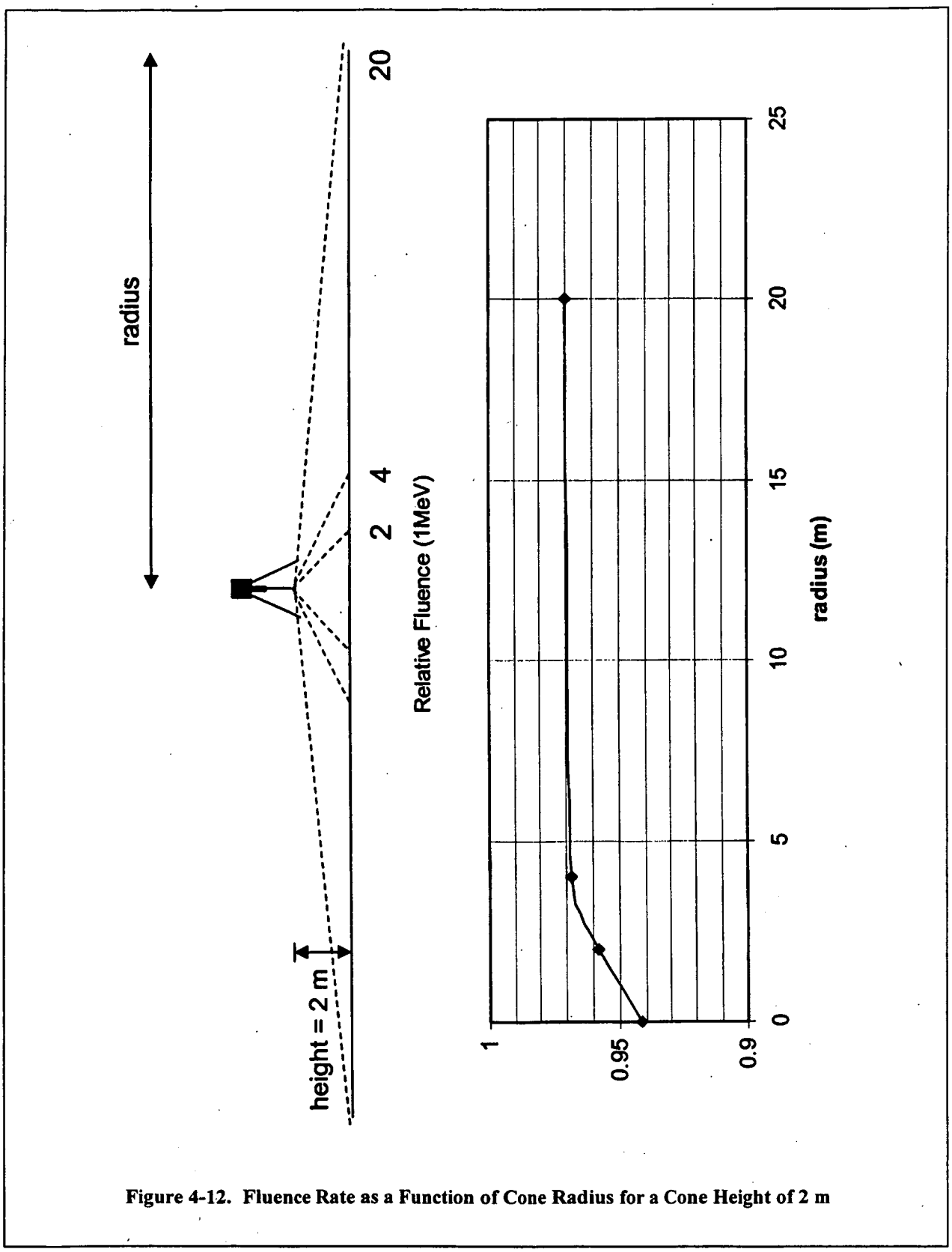


Figure 4-12. Fluence Rate as a Function of Cone Radius for a Cone Height of 2 m

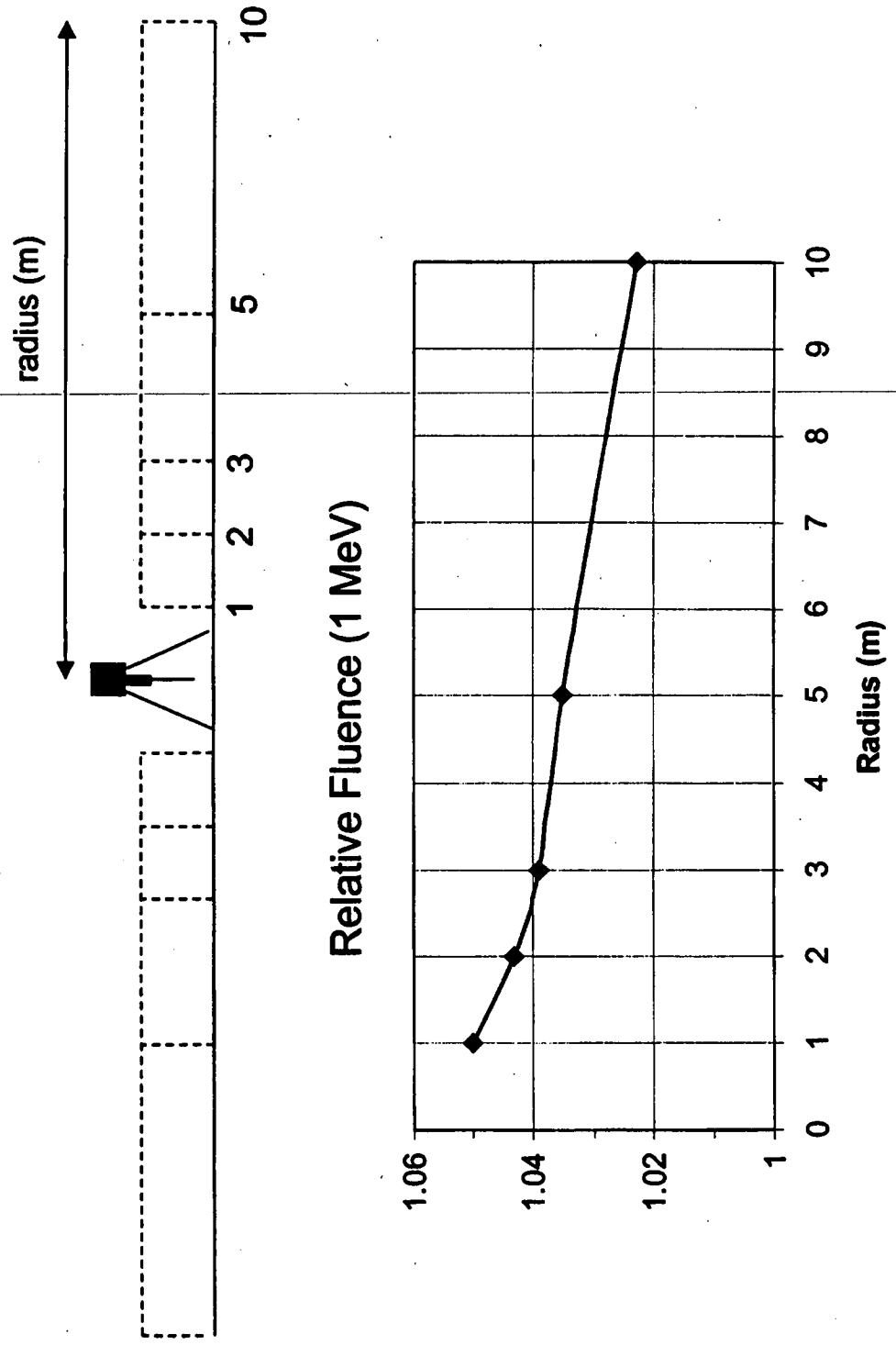
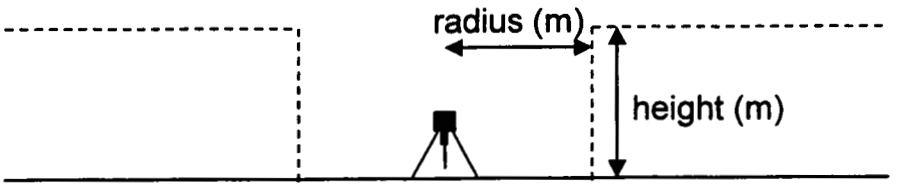


Figure 4-13. Fluence Rate as a Function of Pit Radius for a Pit Height of 1 m



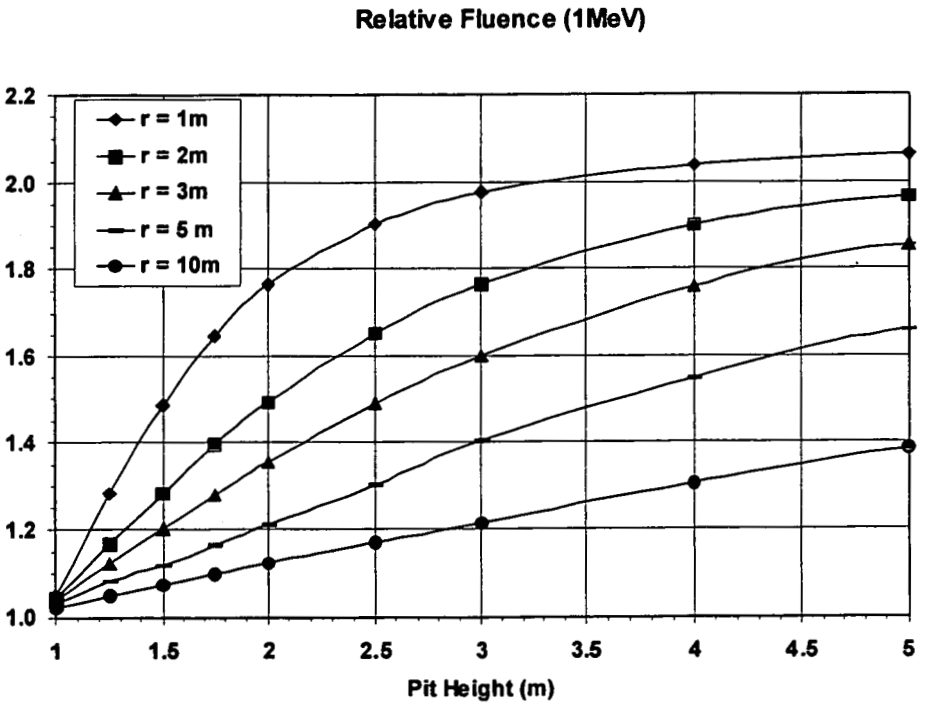


Figure 4-14. Fluence Rate as a Function of Pit Radius and Height

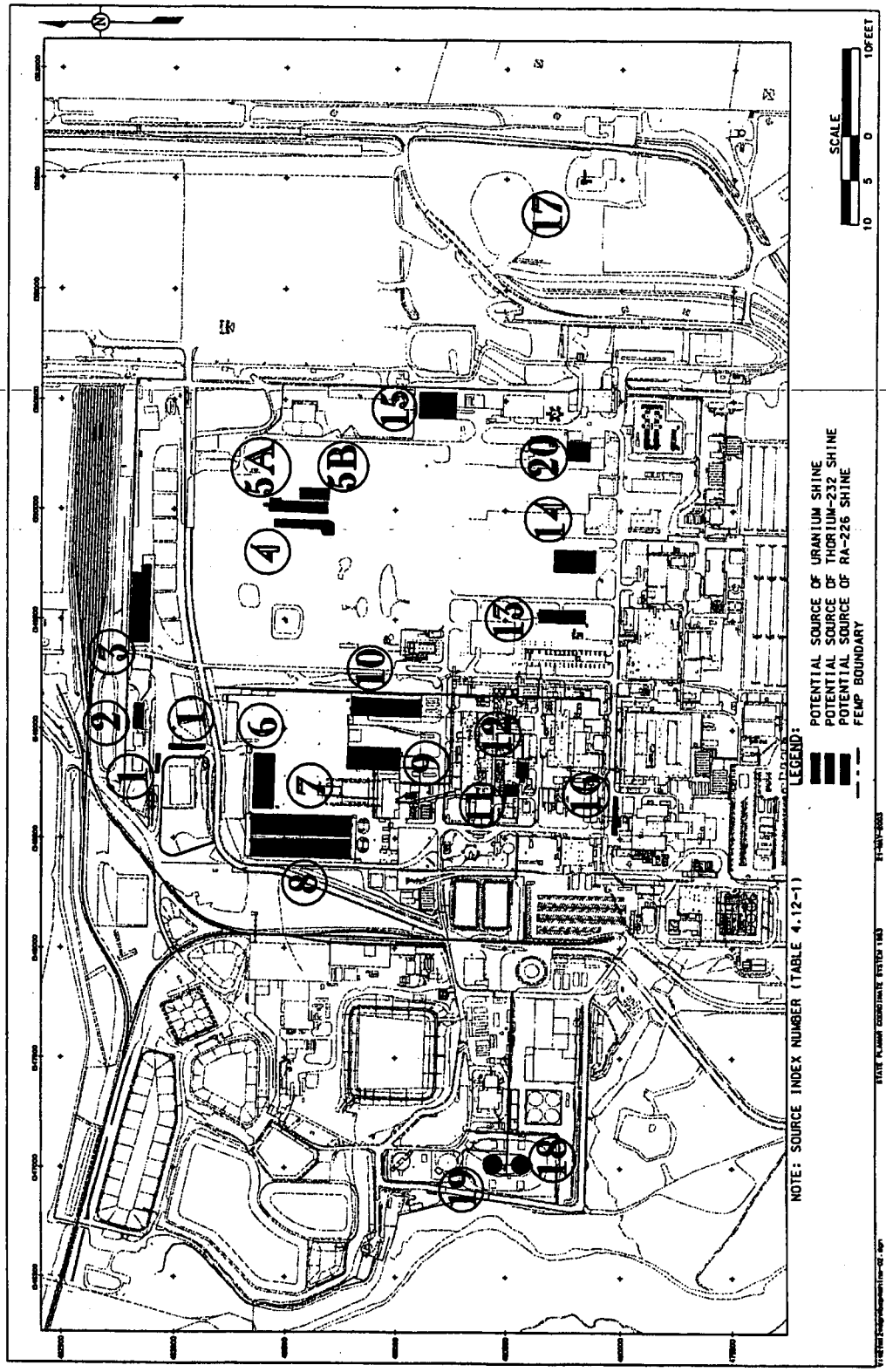


Figure 4-15. Potential Sources of Shine

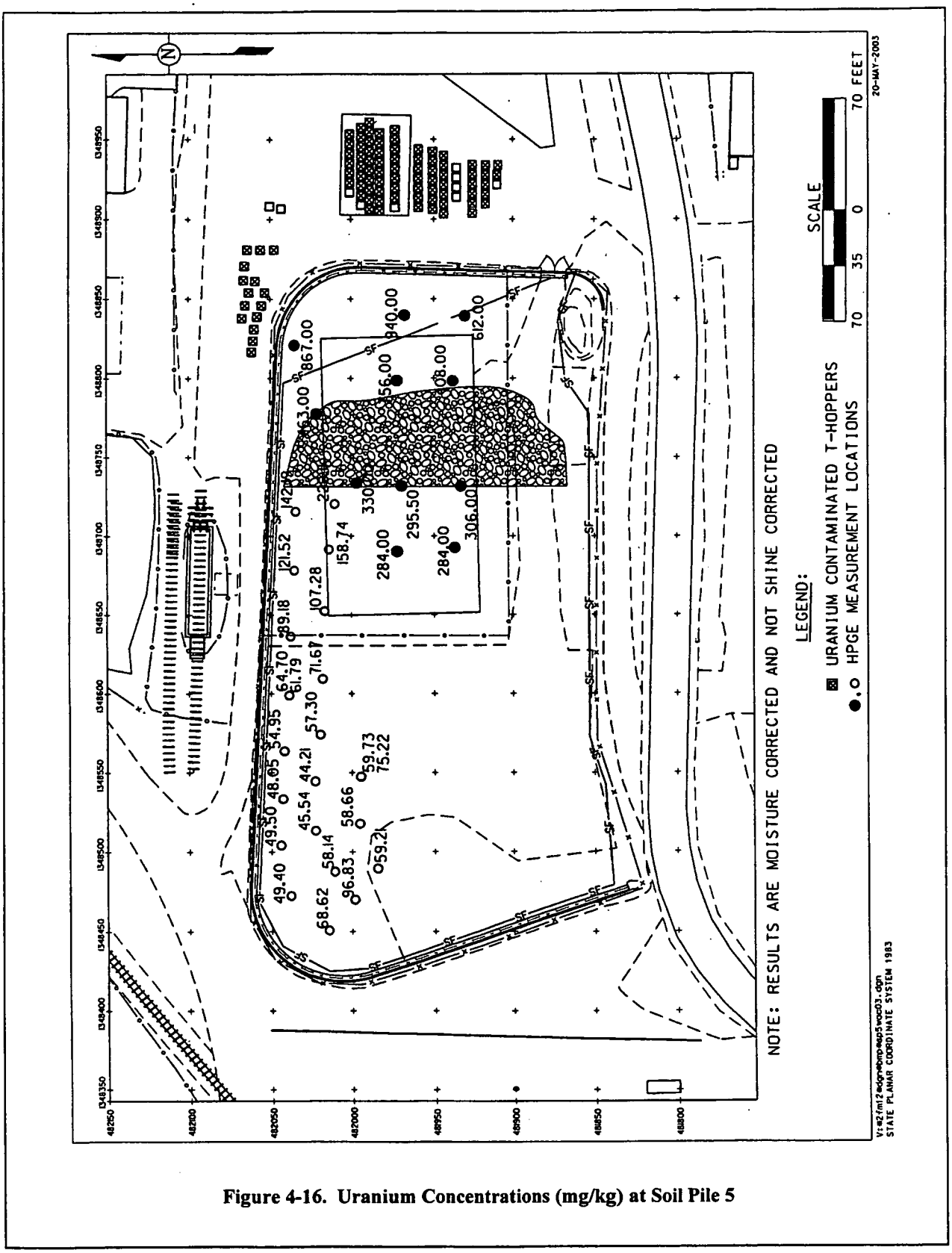


Figure 4-16. Uranium Concentrations (mg/kg) at Soil Pile 5

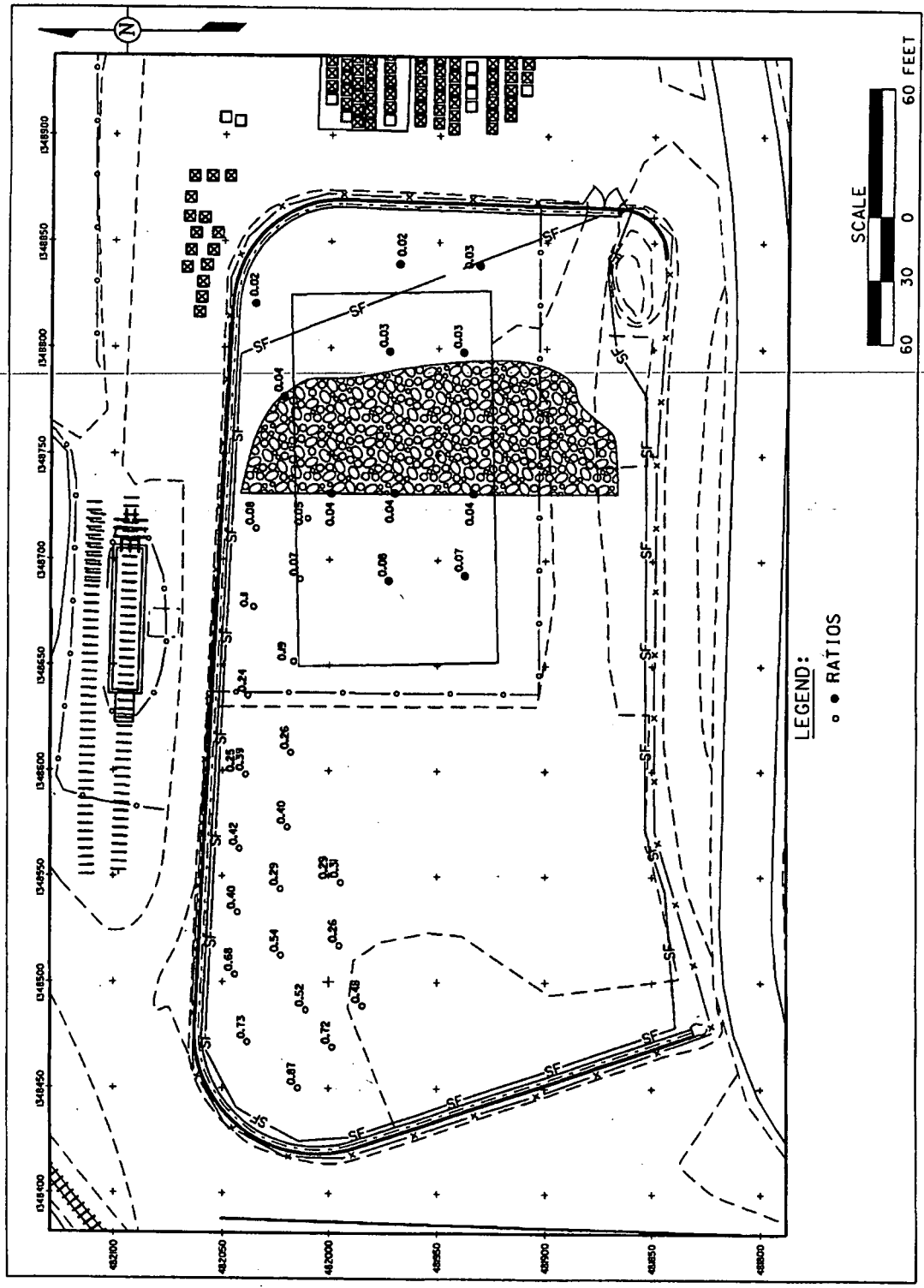


Figure 4-17. Uranium Concentration Ratio for Low to High Energy Photons at Soil Pile 5

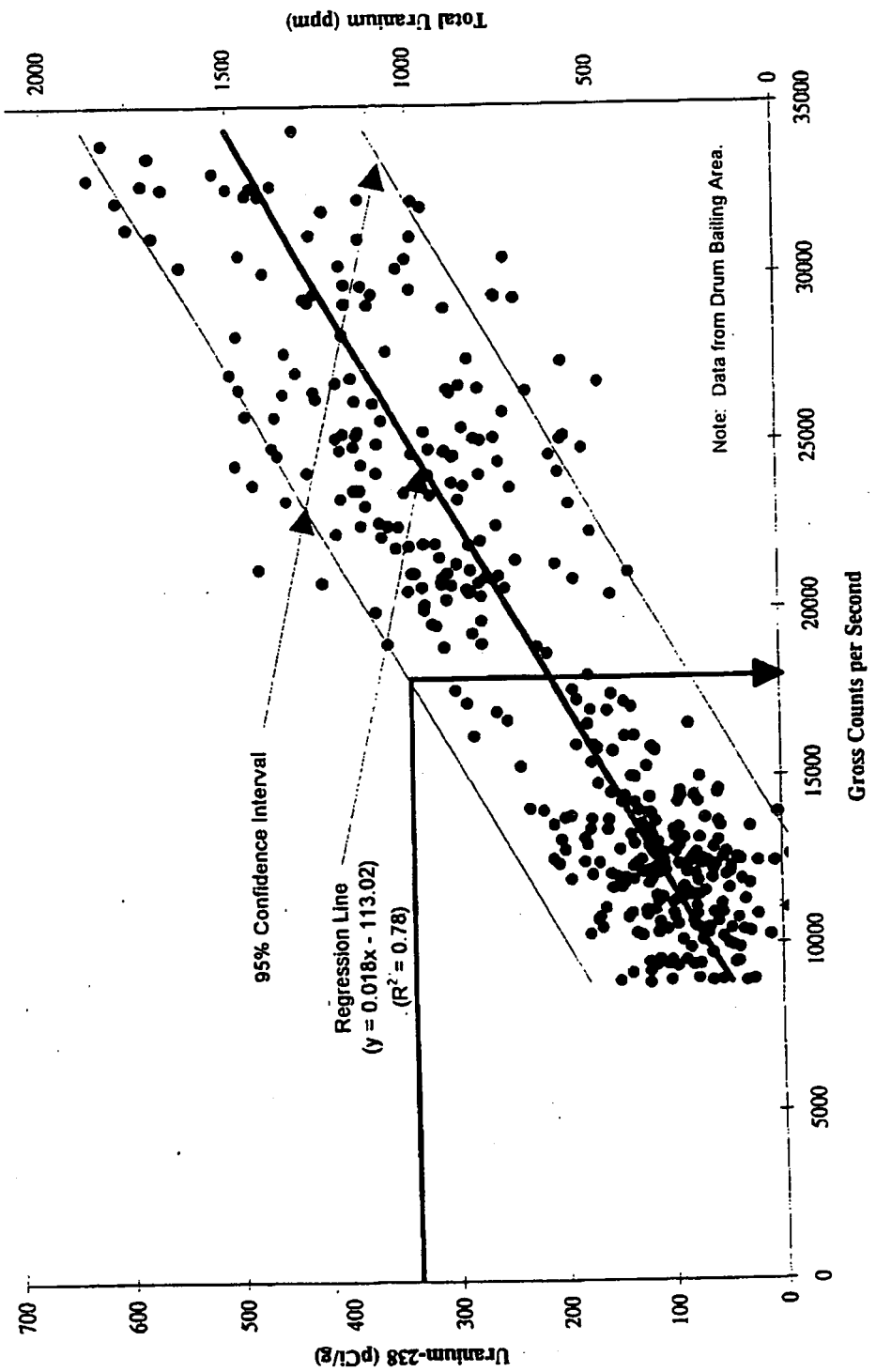


Figure 4-18. Uranium-238 Activity vs. Gross Counts

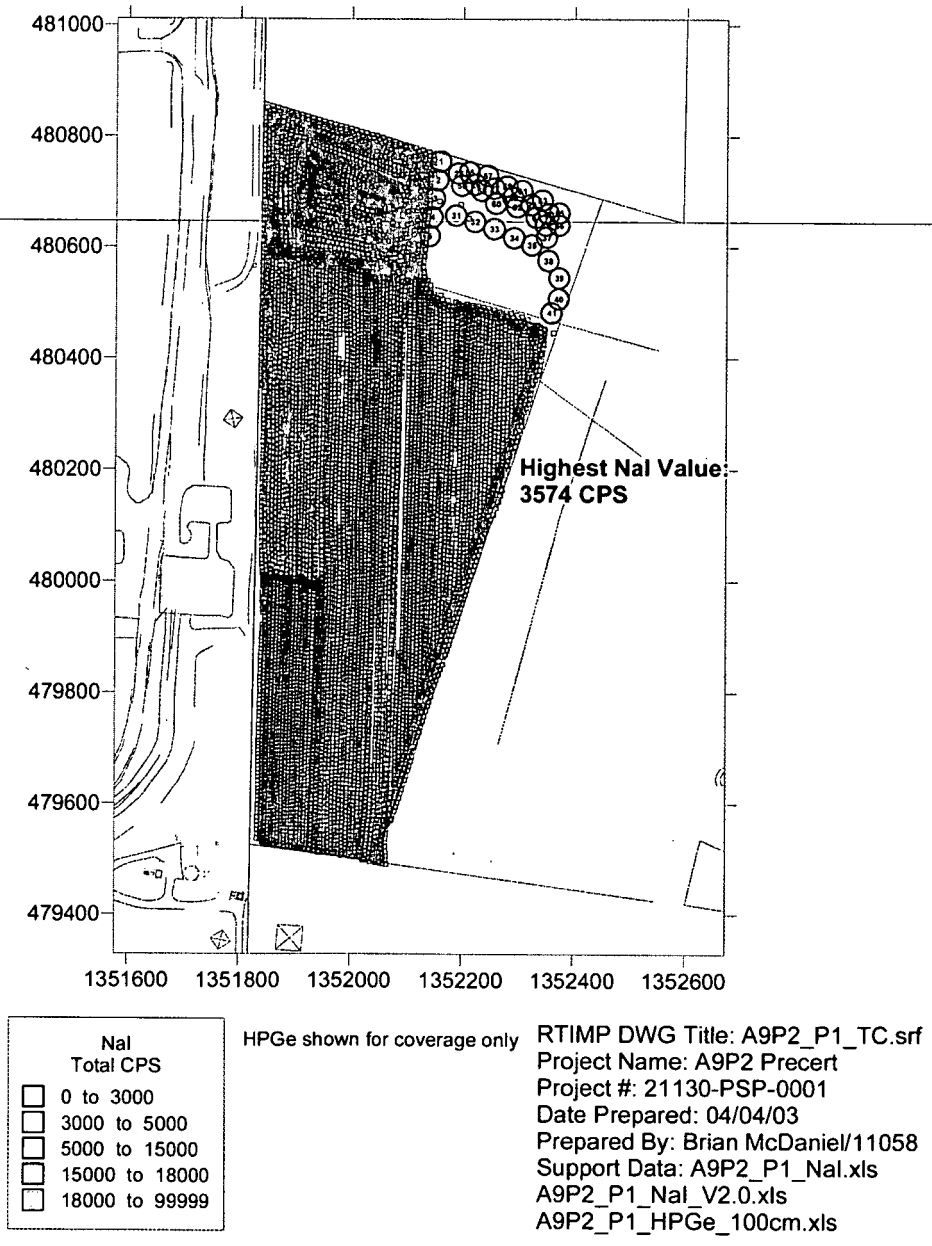


Figure 4-19. Map of Total Gross Counts per Second

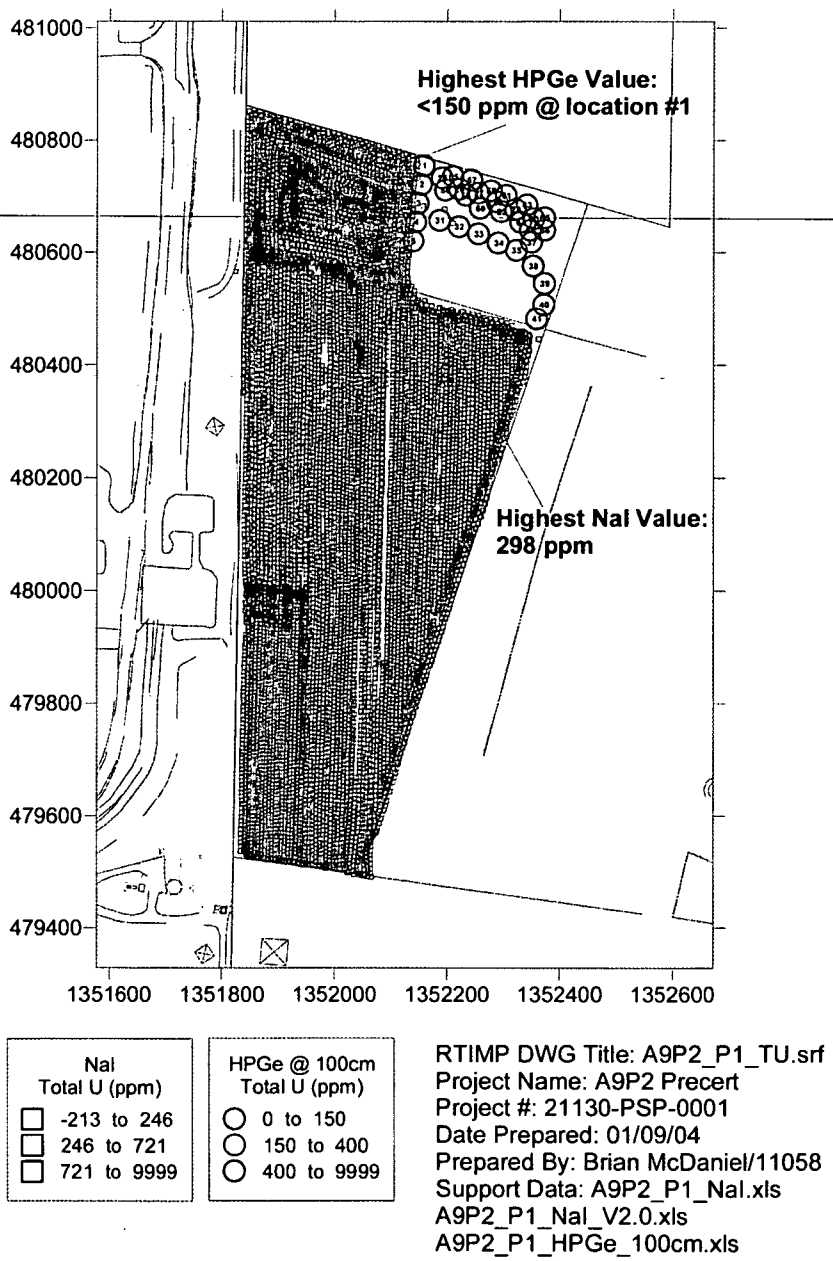


Figure 4-20. Map of Total Uranium Concentration

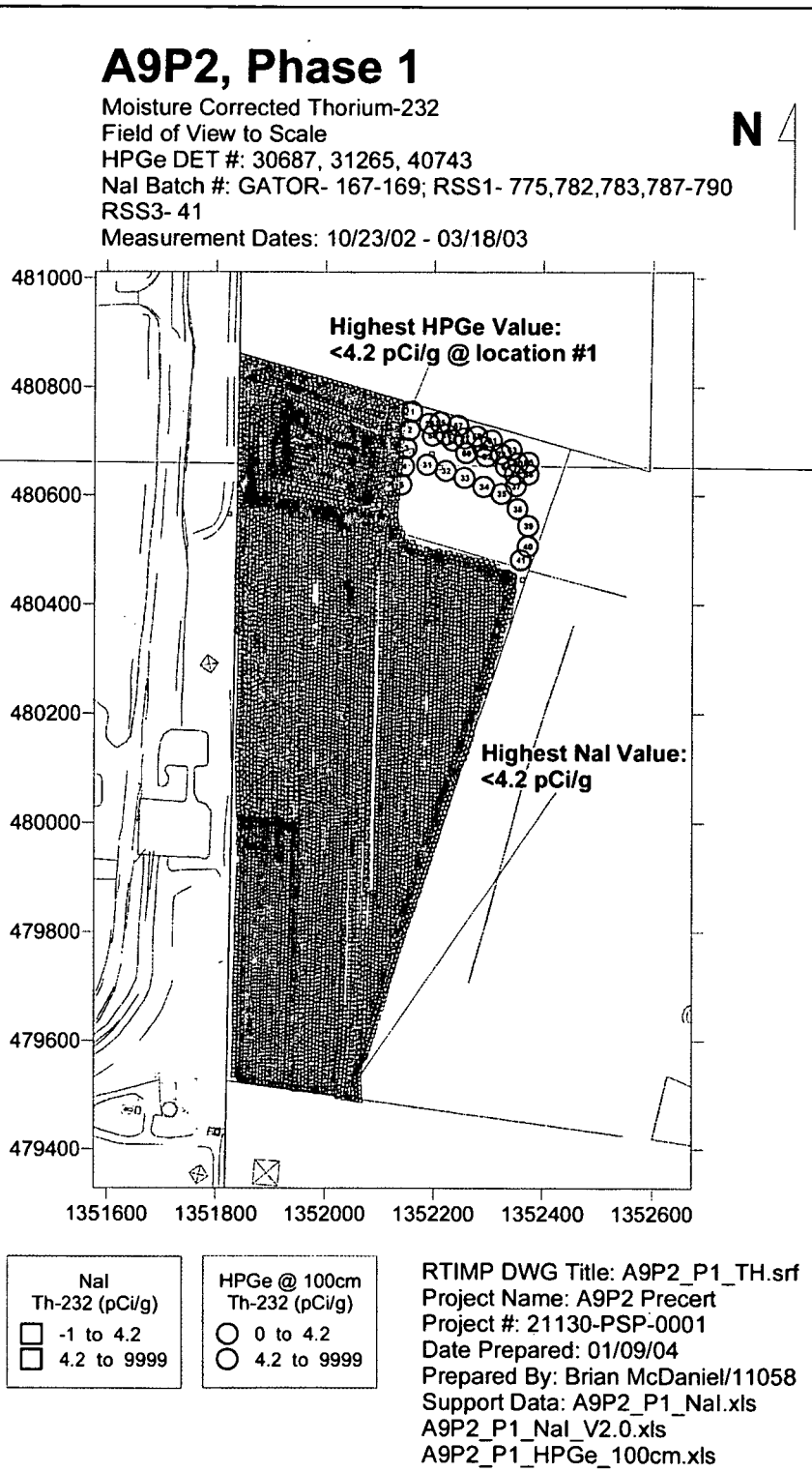


Figure 4-21. Map of Thorium-232 Activity

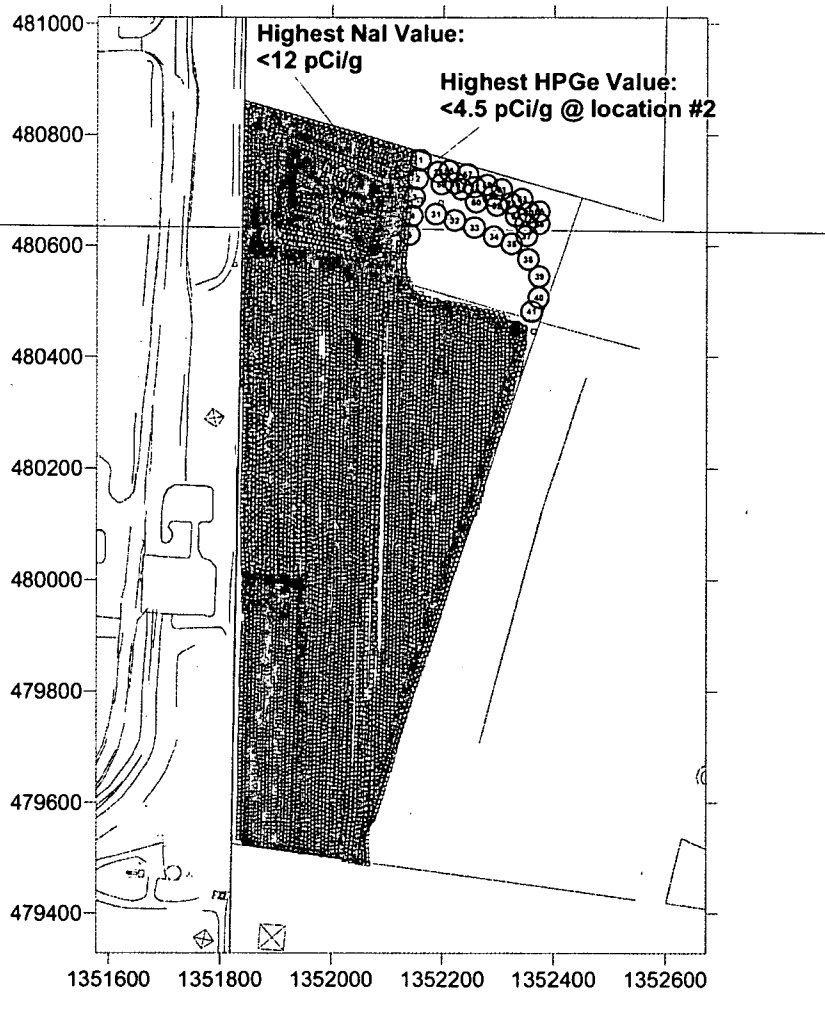


Figure 4-22. Map of Radium-226 Activity

5.0 TECHNICAL TOPICS

Topics included in this section are related to technical aspects of *in situ* gamma spectrometry systems, measurement corrections, and field operations. These topics will be of interest to the end user of *in situ* data and to personnel concerned with collecting the measurements, processing the data, and overseeing data quality.

5.1 RECENT IMPROVEMENTS IN THE NaI SYSTEMS

Since the issuance of the last revision of this manual in January 2004, several significant improvements have been made to the NaI systems used at the FCP. The NaI data analysis software has been improved, and a more accurate determination of the field of view of the NaI detectors has been made. These topics will be described in the following three sections.

5.1.1 Sodium Iodide Gain Tracking

The gain of each NaI detector is determined prior to being used on any given day, as described in Section 4.2. However, the system gain can change during *in situ* measurement operations, due to changes in ambient temperature or excessive vibrations from rough terrain. Such gain drifts would be hard to recognize because well-developed spectral peaks are rarely formed when count times of 4 seconds are employed for *in situ* measurements. When well-defined peaks are present, it is much easier to evaluate gain drift because operators can visually observe whether the peaks are or are not in the expected location.

A new software module has been added to the NaI data processing software to automatically compute the spectrometer gain from spectral peaks that routinely appear in the *in situ* spectra. Before the software can perform this computation, however, multiple spectra must be added together, channel by channel, to form a composite spectrum. The composite spectrum will have enough counts to yield well-shaped peaks, thus permitting an accurate determination of peak centroids and the spectrometer gain. Tests on a number of data sets demonstrate that the addition of 17 spectra is generally adequate to yield a composite spectrum with well defined peaks, allowing an accurate computation of the spectrometer gain. The software was written so that the number of spectra to be added for determining system gain is 17; however, to provide needed flexibility for unusual data sets, the operator can change this number. With the addition of the gain tracking software, an accurate assessment of system gain is made approximately every 4 seconds, rather than once at the start of the day and again at the end of the scanning operation. Although 17 spectra are added together for purposes of computing spectrometer gain (using the most recently acquired spectrum plus the previous 16), spectral analysis to determine the radioactivity content of the

soil is performed on each individual 4-second spectrum. Furthermore, a GPS position measurement is linked with each 4-second spectrum so that the physical location of each 4-second activity measurement is known.

Before gain tracking was implemented, the position of a characteristic peak emitted by one of the contaminants of interest could change significantly, and the peak would no longer be recognized as originating from the isotope of interest because it had drifted outside of its assigned spectral region of interest (ROI). When the peak drifts outside of its assigned ROI, the software assigns an incorrect energy to the peak centroid, leading to the false conclusion that the contaminant was not present in the soil. If the peak drift was less dramatic, so that the peak remained partially within the expected ROI, the software would report an activity on the basis of that peak; but the reported value would be inaccurate because the ROI did not span the entire peak. The likelihood of these situations occurring is much smaller because of the implementation of gain tracking. Each analyte peak has an expected base width, as well as an expected location in a spectrum based on its characteristic energy. As part of the activity computation, the software must determine the total counts in all the memory channels that stored counts from the spectral peak in question. As a spectrometer's gain changes, both the peak centroid location and the peak base width will change. In addition to assigning an accurate energy value to the channel where the peak centroid is located, the gain tracking software also centers the spectral ROI over the peak to ensure all counts are integrated and assigned to the gamma ray in question. The energy limits over which the primary isotopes of interest are integrated are shown in Table 2-4. Each peak will be integrated over the stated energy range (i.e., the ROI), no matter which MCA memory channels correspond to those energies at any given time. The accuracy of the computed activity is directly related to the accuracy in determining the total counts from the associated spectral peak. Thus, on both scores, gain tracking represents an improvement in NaI system accuracy and reliability.

5.1.2 NaI Field of View

This topic has already been discussed in some detail in Section 4.5.2. The NaI field of view radius for a 31 cm detector height was reported in previous revisions of this manual as 1.2 meters; but data evaluated after the Users Manual was updated in January 2004 revealed that the radius of the NaI field of view was actually 2.3 meters. The initial estimate of the NaI field of view radius, 1.2 meters, was made on the basis of point source measurements in which the lack of cylindrical symmetry of the 4"x4"x16" NaI detectors was ignored. If a detector is used in measurement situations where there truly is cylindrical symmetry, then point source measurements to determine the detector's angular response to gamma rays of various

energies, and subsequently the detector's field of view, need only be made in one plane. Because the 4"x4"x16" NaI detectors lack cylindrical symmetry, point source measurements must be made in two perpendicular planes to accurately determine the field of view. When this was done, it was determined that the NaI field of view radius was actually 2.3 meters, instead of 1.2 meters.

It should be pointed out that the initial estimate of the field of view radius (1.2 meters) resulted in very conservative NaI scanning protocols. For example, the normal scanning protocol of having 0.4 meters of overlap and 2 meters between adjacent passes of a NaI vehicle was based on the assumed field of view radius of 1.2 meters (diameter of 2.4 meters). As pointed out in Section 4.5.2, because of the more accurate estimate of 2.3 meters for the field of view radius, the normal NaI protocol has been revised so that there is now 0.6 meters of overlap when adjacent passes of the NaI vehicle are separated by 4 meters. The initial scanning protocol, based on the 1.2-meter radius, resulted in nearly twice as many traverses as was necessary to achieve 100% coverage of the measurement area.

5.1.3 Background Subtraction Using Spectrum Sanding

The 4-second count time chosen for the NaI detectors, which is necessary to achieve the desired spatial resolution, makes it difficult to accurately determine both peak centroid locations and peak backgrounds. However, the technique of constructing a composite spectrum by adding multiple 4-second spectra together may be used to obtain a more accurate estimate of peak backgrounds as well as peak centroids. Determining peak backgrounds from a composite spectrum is accomplished by the following procedure.

1. Add a number of consecutive 4-second spectra together, channel by channel, to form a composite spectrum.
2. Choose a number of channels, w, which corresponds approximately to one half the expected peak base width of a spectral peak at the energy in question.
3. Excluding channels at the extreme ends of the composite spectrum, for each channel, j, average the counts in the w channels above and below channel j. Note that this is an average of the counts in $2w+1$ channels, and $2w+1$ may be referred to as the "sanding window width."
4. Compare the average just computed to the counts in channel j of the composite spectrum. If the average is less than the counts stored in channel j, replace the data in channel j by the average. Otherwise retain the original data in channel j.
5. Move to the next channel (channel $j+1$) and repeat the process.
6. Construct a "sanded spectrum" by repeating the process outlined in Steps 2 through 5 for every channel in the original composite spectrum. Because of the averaging and replacement process, the sanded spectrum will have lower peaks than the original composite spectrum.

7. Repeat the entire sanding process 20 times, each time starting with the spectrum from the previous sanding iteration. The result will be a smooth continuum spectrum with no spectral peaks.
8. Scale the counts in the sanded spectrum to match the data acquisition time of the *in situ* spectrum to be corrected for background. For example, the counts in each channel of the final sanded spectrum should be multiplied by 1/17 if the original composite spectrum was constructed by adding 17 spectra together.
9. To determine the background counts to be subtracted from a selected peak in an *in situ* spectrum, integrate the sanded spectrum (i.e., sum the counts in the sanded spectrum) over the same energy limits that were used to determine the peak gross counts in the *in situ* spectrum.

It is important to bear in mind that the original 4-second *in situ* spectrum is preserved and is ultimately the one on which the analysis results are based. The sanded composite spectrum is constructed only for the purpose of estimating background counts over the energy range corresponding to the original spectrum. The averaging and replacement process removes all the peaks in the original spectrum, much like sanding a piece of wood removes all the high spots, and thus the name "sanding." Figure 5-1 illustrates the effects of the sanding process at several intermediate stages.

Using the sanding technique to determine the background for the spectral peaks of interest results in several improvements. When multiple spectra are used in the sanding process, better background estimates are produced because counting statistics are improved, and the averaging process reduces background fluctuations. Reduced variability in the background brings about lower measurement uncertainties. One large contribution to the measurement uncertainty for the prior method of determining peak backgrounds, using pre-defined fixed background windows above and below each spectral peak of interest, was eliminated when the prior method was replaced by the sanding technique. It is no longer necessary to include a multiplicative factor for scaling the counts in the narrower background windows to the wider signal windows. With sanding, the peak and background windows are the same width. On a practical level, the reduced measurement uncertainty associated with the sanding technique leads to lower detection limits and also allows the establishment of higher WAC trigger levels. Prior to implementing the sanding technique for determining peak backgrounds, a detailed analysis of the NaI measurement uncertainties demonstrated that the 4"x4"x16" NaI detectors were not sensitive enough to detect soil concentrations of uranium at 3*FRL or radium at 7*FRL with a single 4-second measurement. To compensate for these limitations, most NaI results were reported on the basis of eight seconds worth of data in the form of two-point running averages. With the reduced measurement uncertainty associated with implementing the sanding technique for determining peak backgrounds, it is now possible to reliably

detect 3*FRL for U-238, Th-232 and Ra-226 with a single 4-second measurement (ANL 2004) On this basis, the practice of routinely reporting two-point moving average results has been discontinued.

5.1.4 Guidance

- No special operator instructions are needed to employ gain tracking with the NaI data analysis software. The software does this automatically.
- In rare situations, it may be desirable to change the number of spectra to be summed for gain tracking from the default value of seventeen.
- No special operator instructions are needed to employ the spectral sanding background subtraction technique with the NaI data analysis software. The software does this automatically.

5.1.5 See Also

4.2 Daily Energy Calibrations
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
5.4 Minimum Detectable Concentrations

5.2 EFFICIENCY CALIBRATION FOR HPGe SYSTEMS

To relate the count rate from a particular photopeak, N_f, to the activity in the soil, A, a conversion factor must first be determined for the individual detector, the energy of the particular photopeak of interest and the radionuclide distribution. The equation that relates these quantities is

$$\frac{N_f}{A} = \frac{N_0}{\phi} \times \frac{N_f}{N_0} \times \frac{\phi}{A}$$

where: N_f/A = count rate of photopeak of interest (at energy E) per unit activity of that isotope in the soil (counts/sec per pCi/g),

N_0/ϕ = photopeak count rate per unit photon flux incident normally on the detector face (counts/sec per photons/cm^2/sec),

N_f/N_0 = a unitless angular correction factor which varies with photon energy.

ϕ /A = photon flux at the detector for the gamma ray of interest per unit activity of the isotope of interest in the soil (photons/cm^2/sec per pCi/g).

The first two factors on the right side of the equation depend solely on the properties of the particular detector, while the third factor, ϕ /A, depends on the properties and the geometry of the gamma ray

source, the soil half space in our case. The ϕ /A factors are derived from gamma ray transport calculations, and tabulations of these factors may be found in the scientific literature. Both N_0/ϕ and N_f/N_0 can be determined experimentally by counting a series of point sources that emit gamma rays of differing energies at angles varying from 0° (normal to the detector face) to 90° (parallel to the detector face). From these measurements, smooth curves can be developed which provide the variation of N_0/ϕ and N_f/N_0 with angle and with photon energy.

N_f/A, (counts per sec./pCi/g) is the desired factor that is used to convert peak net count rates to activity. The activity per unit mass in the soil is obtained when the spectral peak net count rate (counts per sec.) is divided by the conversion factor,

$$A(pCi/g) = \frac{N_f\,(counts/\sec)}{N_f/A(counts/\sec)/(pCi/g)}$$

The process of "calibrating" an HPGe detector for *in situ* gamma spectrometry consists of determining N_f/A at various energies and developing a smooth curve to represent the discreet data points so that an appropriate conversion factor may be computed for any energy of interest.

5.3 EFFICIENCY CALIBRATION OF NaI SYSTEMS

By analogy with standard practice in radiochemistry laboratories, RTIMP procedures require annual efficiency calibration for all NaI and HPGe *in situ* gamma detectors. Calibration of RTIMP NaI detectors is currently accomplished by deploying multiple sets of specially prepared single-isotope radionlucide standards in a specific pattern on the RTIMP calibration pad. The calibration pad was designed so that when a set of forty-five single-isotope standards is deployed in a bull's-eye pattern on the calibration pad, the gamma flux from the standards approximates the flux from a uniformly contaminated land area. Separate sets of U-238, Th-232 and Ra-226 standards were prepared for the calibration pad so that detector response to each of the primary gamma-emitting isotopes of concern could be measured directly. The design, construction and use of the RTIMP calibration pad are described in detail in the report "Calibration of NaI *In situ* Gamma Spectroscopy Systems," March 2001, hereafter called the "NaI calibration report." The calibration pad not only allowed a direct determination of detector responses to each isotope, it also allowed unambiguous measurements of the magnitude of the spectral interferences that each calibration isotope contributed in the spectral regions of the other isotopes.

By way of background information, prior to the availability of the calibration pad, NaI systems were calibrated by making measurements at multiple locations around the FCP with varying levels of radionuclide contamination. The locations were carefully characterized using *in situ* HPGe systems, which were calibrated to NIST traceable standards, producing, in effect, secondary field standards. Such "field calibrations" of the NaI systems, while producing acceptable calibrations, were less than ideal. It was not always possible to find field locations that had the range of contamination levels desirable for calibration purposes. While there were an abundance of locations with low levels of contamination, there were much fewer areas with elevated contamination levels. In addition spectral interferences were sometimes present in areas with higher contaminant levels, making these areas less than ideal for calibration purposes. At some field locations, particularly those with higher concentrations, the isotopes of concern were not homogeneously distributed, also making them less than ideal for calibration purposes. Moreover, locations with elevated contamination were being eliminated as soil remediation proceeded.

The overhaul of the NaI calibration approach was conducted mainly in CY2000, culminating with a draft report in October 2000 and a final report in March 2001. Two different and independent calibration procedures were performed: a point source calibration and a calibration using a calibration pad. The point source calibration involved adapting an industry-accepted procedure that employed multiple gamma ray sources of known isotopic content to make measurements at various angles to the face of the NaI crystal. The sources used, Cs-137, Sn-113, and Y-88, emitted primary gamma rays with energies from 391 to 1836 keV, covering most of the range of interest for the primary soil contaminants: U-238, Ra-226 and Th-232. These point sources were traceable to NIST.

The point source calibration method for NaI detectors is analogous to the method used to calibrate the RTIMP HPGe detectors. The equation which relates the fundamental quantities of interest for deriving conversion factors to compute isotopic activities in the soil from observed net peak count rates is the same for both the NaI and the HPGe point source calibrations. This equation was presented in Section 5.2. However, because the NaI detectors used at the FCP lack the cylindrical symmetry of the HPGe detectors, point source measurements must be made at a series of angles in two perpendicular planes that pass through the center of the NaI crystal.

The two NaI calibration methods are separate and independent with respect to the determination of conversion factors that relate net peak count rates to radionuclide concentrations in the soil. The

two calibration techniques make use of different radionuclide standards. The point source calibration can serve as verification of the calibration performed with the calibration pad. The point source calibration is linked only peripherally to the pad calibration in that the Ra-226, Th-232 and U-238 sources fabricated for the calibration pad were used to determine interference correction coefficients that are used when the point source calibration is applied to derive activity from gamma spectral measurements of the soil. In both the point source and pad calibration techniques, net count rates in the spectral regions of interest must be corrected for contributions from other interfering isotopes. These correction factors are simply the ratios of the net counts that accumulate in two different spectral regions from one isotope. For example, when quantifying uranium, some of the counts that accumulate in the U-238 spectral window may be due to Th-232 daughter interferences. The thorium interference correction factor is simply the ratio of counts in the uranium window divided by the counts in the thorium window when only a thorium source is present. In the derivation of this type of interference correction factor, the activity of the standard used is immaterial as long as it is large enough to provide enough counts in a reasonable length of time. Such a use of the calibration pad standards in the point source calibration does not negate the independence of the two techniques.

Section 4 of the NaI calibration report presents comparisons of the results from the point source and pad calibrations, as well as comparisons of *in situ* measurement results from a number of remediation locations. Soil activities were calculated on the basis of both point source and pad calibrations, and these were compared to HPGe measurements performed at the same locations and to results generated by the supplanted field calibration technique. Both point and pad calibration results agreed quite well with the HPGe measurements, and were closer to HPGe than results based on the original field calibration technique. The degree of agreement among the measurement results based on HPGe, pad, and point source calibrations demonstrates very effectively the superiority of these two techniques over the technique of using field locations to derive NaI detector calibrations. This analysis established the validity of both the point source and pad calibration methods. Both techniques are superior to the field calibration technique, because they agree more closely with HPGe measurements and they can be performed repeatedly in a reproducible manner, without regard to the progress being made in the remediation of the soil at Fernald.

5.3.1 Use of the Calibration Pad

The underlying concept behind the creation of the FCP calibration pad is that a uniformly contaminated layer of soil can be simulated by placing a number of discreet radionuclide standards in a reproducible

array in an otherwise "clean" volume of soil. The gamma ray flux from the individual sources combines to create an overall gamma field. The number and position of the standards was chosen to approximate the flux of gamma rays from a uniformly contaminated volume of soil The construction of a calibration pad required the preparation of calibration standards. Because of the large quantities of uranium, radium and thorium required, Fernald staff produced the pad standards from available site materials. Sufficient quantities were needed to produce a pad with an area somewhat larger than the field of view of a stationary NaI detector at the standard detector height of 31 cm. Another objective was to use enough radioactive material to simulate an average activity concentration over the pad well above cleanup levels. Standards were prepared using site materials of known composition, which were mixed with low-density resin beads to yield a composite material of a density similar to soil. The homogenized mixture was packed in 1.25 x 6-inch plastic tubes to produce the standards. Forty-five such tubes (plus five spares) were prepared for each of the isotopes: U-238, Ra-226 and Th-232. The tubes were assayed in the on-site laboratory using gamma spectroscopy, and thereby are secondary standards.

The standards are placed in a 360-degree circular pattern in the calibration pad simulating a large flat homogeneously contaminated soil source. During the construction of the pad, capped plastic source holders were embedded vertically in the pad soil to provide a means of reproducibly deploying the standards. When deploying the sources, the caps are removed from the source holders and the sources are inserted so that their tops are flush with the pad surface. With a full compliment of 45 standards placed in the pad, a detector at the center of the pad would see effective soil concentration of 326.5 pCi/g of U-238, 20.37 pCi/g of Ra-226, or 9.045 pCi/g of Th-232.

The exact placement of the standards in the pad is described in Appendix B of the NaI Calibration Report (DOE 2000). Briefly, the standards are placed in seven concentric circles containing from one to eight evenly spaced sources beginning at the center of the bull's eye and extending out to 207 cm. Each source represents the same area of soil, 3292 cm^2. The sources are placed along common transects to facilitate the movement of detector systems and personnel over the pad.

To perform a calibration, a NaI detection system is placed directly over the center standard, at the normal detector height of 31 cm. Four measurements are needed to perform a complete calibration: a background measurement plus one measurement of each of the three sets of isotopic standards. The calibration pad is loaded with tubes containing soil for the background measurement, then sequentially with each set of 45 standards of the three primary isotopes. Five-minute gamma ray spectra are collected for each measurement.

The measurement data collected are used to determine the detector response to each calibration isotope. This involves determining a set of efficiency coefficients and interference coefficients for each primary isotope. As discussed more fully in the NaI calibration report, studies were conducted to determine the most advantageous placement of the spectral regions to be used in determining peak net count rates from the various isotopic standards. The ROIs that were ultimately selected were a compromise between maximizing counts from the calibration isotope and minimizing gamma ray counts from possible interfering radionuclides. Currently, energy gain tracking is used to ensure that ROIs are shifted to the proper channel numbers if the system gain (in KeV/channel) changes relative to its value in the initial calibration. Therefore, ROIs may shift slightly from day to day, while ROI widths in terms of energy remain constant. Also, a new technique for determining the background contribution to spectral peaks has been implemented. With this new "sanding" technique, it is no longer necessary to determine background counts from precisely defined background windows above and below each spectral peak of interest. The background window for any peak is now the same as the signal window used to quantify each isotope of interest.

Calibration measurements of individual sets of isotope standards yield efficiency coefficients for each primary isotope and K-40, and 13 interference coefficients associated with the same four isotopes. These coefficients, in turn, are used to determine, for a given gamma detection system, a set of calibration coefficients for each of the three primary isotopes and potassium (K-40). Potassium-40 is a naturally occurring isotope that is present in all soil. The spectral peak from this isotope is very useful for a rapid assessment of the quality of spectral data.

The detector efficiency coefficients are determined as the net count rates in the ROI for a given isotope per pCi/g of effective concentration in the calibration pad soil. Interference coefficients are determined as the fraction of gamma rays of the interfering isotope appearing in the ROI of the isotope of interest. As described in Appendix A of the NaI Calibration Report (DOE 2000), the interference coefficients to be applied to actual field measurements are determined by solving a set of simultaneous equations, which account for mutual interference of three primary isotopes. Interference factors are applied to the raw net counts (after background subtraction) in the ROI of each isotope to determine the corrected net counts. Dividing the corrected net counts produced by a calibration measurement by the efficiency yields the calibration coefficient.

5.3.2 Revising the Calibration Coefficients

While the calibration process may be expected to yield a set of conversion factors and interference coefficients that are similar, things such as shielding due to the vehicle and detector mounting, the age of the detector crystal and slight differences in the condition of the signal processing electronics, will result in slightly different factors from one detector to another. As a consequence, detector-specific coefficients must be stored in the gamma spectrometry software and used in the computation of radionuclide activity. In accordance with the RTIMP Quality Assurance Plan and procedures, each NaI platform must be recalibrated annually. After measurements are performed on the calibration pad and conversion factors and interference coefficients are calculated, the newly derived parameters are compared to the values currently in use to ascertain if there have been significant changes. If significant changes are noted, an attempt will be made to determine the cause of the change before using the new calibration parameters.

5.3.3 Guidance

- Calibrate any new NaI detection system on the RTIMP calibration pad prior to initial use.
- Using the calibration pad, perform an annual recalibration of each NaI detection system to be used in a given excavation season, preferably at the beginning of the excavation season.
- Refer to the RTIMP Operations Manual, RTIMP-M-003, for instructions on performing NaI detector calibrations on the calibration pad.

5.3.4 See Also

2.0 *In situ* Gamma Systems Operated at the FCP
5.3 Minimum Detectable Concentration

5.4 MINIMUM DETECTABLE CONCENTRATION

In general terms, Minimum Detectable Concentration (MDC) is related to the detection sensitivity of an analytical instrument or procedure. As used in this manual, it refers to the ability of HPGe and NaI *in situ* gamma spectrometry systems to detect low levels of the radionuclides of interest at the FCP. The MDC is an *a priori* estimate of the minimum net activity level that can be measured reliably by an *in situ* gamma spectrometry system under a typical set of operating conditions. The U.S. Nuclear Regulatory Commission (NRC), EPA, DOE and DOD defines MDC as the net activity level that can be expected to be detected 95% of the time (NRC 2000). An *a priori* estimate of the minimum net count rate that can be distinguished from instrument background or a blank count rate with 95% confidence is termed the instrument detection limit, L_D. The MDC is determined by multiplying L_D (counts) by appropriate conversion factors to give units of activity per unit mass, i.e., pCi/g. MDCs and detection limits are industry-accepted quantities for specifying instrument detection sensitivities. Detailed

information on the MDCs of the HPGe and NaI instruments used at the FCP may be obtained from two reports: "HPGe Comparability Study" (DOE 1999a) and "Measurement Uncertainties and Minimum Detectable Concentrations for the *In Situ* NaI Gamma Spectroscopy Systems Used at the Fernald Site" (ANL 2004). While the methods for determining HPGe and NaI MDCs are the same as described in these reports, MDC values are updated annually, with the most recent values given in this report. It would be meaningless to compare measurement results to regulatory limits if the measurement system was not sensitive enough to detect analyte concentrations at the regulatory limit. So detector MDCs are a crucial element in assessing the technical adequacy of the *in situ* measurements program at the FCP.

5.4.1 HPGe MDCs

HPGe detector MDCs are determined by collecting a series of gamma ray spectra in a low background area. MDCs are calculated from the standard deviation of the background counts for each isotopic photopeak of interest by the well-known equation

$$MDC_i = \frac{2.71 + 4.65 \times s_b}{LT \times Y \times K}$$

where MDC_i = minimum detectable concentration for photopeak i
s_b = standard deviation of background counts obtained from the spectral region of interest (ROI)
LT = live count time in seconds
Y = gamma yield for the photon of interest
K = conversion (efficiency) factor for the corresponding photon energy

When more than one photopeak is used to quantify a given isotope, the isotopic MDC is computed from a pooled standard deviation derived from the individual photopeak standard deviations.

Table 5-1 presents typical MDC values for the HPGe detectors used at the FCP. For comparison purposes, the table also displays FRL values for the same isotopes. FRLs are the lowest, and therefore, the most difficult regulatory limit to satisfy. By presenting the HPGe MDCs and FRLs side by side, the reader can easily see that the FCP *in situ* HPGe detectors have the sensitivity to detect the analytes of concern when those analytes are present at concentrations equal to the FRL regulatory limit. MDCs for both 5 and 15-minute count times are displayed in the table. The MDC values displayed in Table 5-1 were derived from the most recent annual MDC update. Whereas in the past, fifteen-minute measurements were used to derive individual HPGe detector MDCs, the most recent annual MDC update

was based on five-minute counts. The 15-minute MDC values were obtained by dividing the five-minute MDCs by the factor 1.732, which is the square root of the ratio of the two count times. However, these calculated 15-minute MDCs are, in fact, quite similar to the 15-minute MDC values reported in prior revisions of this manual. The data presented in Table 5-1 lead to the conclusion that the RTIMP HPGe detectors have the sensitivity required to satisfy even the most restrictive regulatory limits (i.e., FRLs) for all isotopes with a five-minute count time. This is the basis for adopting the five-minute count time as the standard time for HPGe measurements. If special circumstances require it, longer count times could be employed to achieve greater measurement sensitivity.

5.4.2 NaI MDCs

The same issues regarding HPGe detector MDCs relative to regulatory limits also apply to NaI detectors. That is, in order to be assured that these instruments are sensitive enough to make reliable judgments regarding compliance with regulatory limits, the MDCs of these systems must be below the regulatory limits of concern. Because of the inherently higher background in the larger FCP NaI detectors, the MDCs for these systems can be expected to be considerably higher than HPGe MDCs. Indeed, it turns out that the MDCs of the mobile NaI systems are not low enough to reliably judge compliance with FRL limits. NaI instrument MDCs are updated annually, usually when the instrument is calibrated. The current NaI instrument MDCs are listed in Table 5-2.

Minimum detectable concentrations for the NaI platforms are determined annually by performing background measurements on the RTIMP calibration pad. The calibration pad was designed to simulate a uniformly contaminated area larger than the field of view of the detectors to be calibrated. For NaI detectors the stationary field of view is approximately 16.6 m^2, with the detector at a fixed height of 31 cm above the ground. The process of deriving MDCs for the NaI platforms from the measurements performed on the calibration pad is described in detail in the reference ANL 2004. As described in that report, the minimum amount of a given isotope that can be detected is affected by other isotopes that are present. For example, if the level of Th-232 in the soil is elevated, the high energy gamma ray which indicates the presence of Th-232 (the 2614.6 keV gamma ray emitted by Tl-208, a Th-232 daughter) will cause more counts to accumulate in the U-238 spectral region of interest (ROI) because of Compton scattering. With increased counts in the U-238 spectral ROI, the calculated uranium activity and MDC will be higher than if the Th-232 was not present. Because of this phenomenon, the determination of NaI platform MDCs involves a series of calibration pad measurements with uranium, thorium and radium sources sequentially deployed, in addition to background measurements with blank sources deployed.

Table 5-2 compares NaI platform MDCs to regulatory limits. It is evident from the uranium MDC values displayed in Table 5-2 that the NaI platforms generally do not have the sensitivity to detect uranium when it is present at a concentration equal to the FRL. This is due in large measure to the shorter count times employed for NaI measurements. Lower NaI MDCs can be achieved if count times are extended, but this will result in a corresponding decrease in spatial resolution. The table also shows that FRL concentrations of Th-232 are detectable with any NaI platform except RTRAK and that Ra-226 FRL concentrations are detectable with any platform except GATOR.

It is good practice to require that an instrument selected for a particular measurement have a detection limit below the regulatory limit of concern. This will provide a margin of safety regarding the detectability of the analyte of interest. Table 5-2 reveals that for certain instrument/isotope combinations, there is no margin of safety between the instrument MDC and the FRL concentration. It is for this reason that the lowest action level that is evaluated with any of the NaI systems is 3*FRL. It can be seen that there is a significant margin of safety between the NaI MDCs and the 3*FRL regulatory limit (i.e., the hot spot criterion) for all of the NaI detectors and for all isotopic hotspots, except for uranium hot spots in areas where the FRL is below 82 mg/kg.

Any additional uncertainty associated with a measurement will cause an increase in the computed value of the MDC. For Ra-226 measurements, the process of correcting measurement results to compensate for radon disequilibrium in the soil increases the uncertainty of the Ra-226 results. The Ra-226 MDCs displayed in Table 5-2 have been processed like any other *in situ* Ra-226 data. That is, first a "wet weight" value is computed from the raw count data, then the Lab-Field correction is applied to the wet weight MDC to compensate for the low bias in *in situ* Ra-226 measurement results relative to laboratory analyses, and finally the "radon corrected" MDC is converted to a dry weight MDC. The application of these corrections generally yields dry weight MDCs that are larger than the wet weight MDC. For details see reference ANL 2004. Despite the increased measurement uncertainty that results from correction of field measurements for radon disequiliibrium, Ra-226 MDCs are well below 5.1 pCi/g, the radium hot spot criterion.

As a further safety measure, HPGe measurements are performed at the location of the highest NaI result for each isotope that exceeds 3*FRL. Additionally, an HPGe reading is taken at the location of the highest NaI gross count value. These confirmatory HPGe measurements could occur at four separate locations if the elevated NaI isotopic and total activity readings occurred at different locations. Any

location where the confirmatory HPGe measurements show radionuclide concentrations in excess of three times FRL is treated as a hot spot. As long as the HPGe measurements continue to confirm that the elevated NaI readings did exceed 3*FRL for one or more isotope, the next lowest NaI reading for that isotope or total activity will be investigated with an HPGe detector.

5.4.3 Guidance

- To ensure that an *in situ* measurement system has the sensitivity to detect activity at a given regulatory limit such as FRL or hot spot criteria, the instrument MDC should be less than the regulatory limit in question. Instruments that do not have the sensitivity required to detect analyte concentrations at the regulatory limits should not be used to determine compliance with the limits.
- HPGe MDCs are sufficiently low for all isotopes to permit HPGe measurements to be used to evaluate compliance with all soil regulatory limits.
- NaI MDCs do not permit these detectors to be used to evaluate compliance with FRL criteria. However, NaI detectors do have the sensitivity required to judge compliance with hot spot criteria. As a precautionary measure, NaI hot spot exceedances are confirmed by HPGe measurements.
- To confirm NaI measurement results that indicate hot spot exceedances, HPGe measurements are performed at the location of the highest NaI total activity and at locations where the NaI results exceed 3*FRL, starting with the highest result for each isotope.
- As long as the HPGe measurements confirm that the NaI results exceeded one of the hot spot criteria, confirmatory HPGe measurements will continue at the next lowest NaI result.
- To ensure that an *in situ* measurement system has the sensitivity to detect activity at a given regulatory limit such as FRL or hot spot criteria, the instrument MDC should be less than the regulatory limit in question. Instruments that do not have the sensitivity required to detect analyte concentrations at the regulatory limits should not be used to determine compliance with the limits.
- Annually compute *in situ* detector MDCs on a dry weight basis.

5.4.4 See Also

4.5 Detector Field of View and Area Coverage
4.7 HPGe Data Acquisition Time
4.15 Mapping Conventions

5. 5 MOISTURE CORRECTED DATA

Because *in situ* measurement results are reported as radionuclide concentrations, that is, on a per gram basis, the amount of moisture in the soil can have a significant effect on the reported values. To illustrate this point, if a ten gram sample, consisting of 2 grams of water and 8 grams of dry soil, contained 100 pCi of Th-232, the wet-weight Th-232 concentration would be 10 pCi/g (100 pCi/10 g), whereas the

dry-weight concentration would be 12.5 pCi/g (100 pCi/8 g). This amounts to a 25% difference in the reported value.

Sample moisture content can be specified in two ways: on a wet sample weight basis or on a dry sample weight basis. Using the example above, the wet-base moisture content of the soil would be specified as

$$M_{WB} = \frac{weight\ of\ water\ in\ soil}{wet\ weight\ of\ soil} = \frac{2}{10} = 0.2,$$

whereas the dry-base soil moisture would be

$$M_{DB} = \frac{weight\ of\ water\ in\ soil}{dry\ weight\ of\ soil} = \frac{2}{8} = 0.25.$$

Because of the instrumentation available when the Real Time Measurements Program was started, all RTIMP moisture measurements are DRY-BASE moisture measurements.

In situ gamma spectrometry systems sense incident gamma flux regardless of the soil moisture content and report the radionuclide concentration on an "as is" or "wet weight" basis. These results may be converted to a dry weight basis by using the following equation:

$$C_{DB} = C_{WB} \times (1 + M_{DB})$$

where: C_{WB} = "as is" radionuclide concentration reported by the gamma spectrometry system (pCi/g wet)

M_{DB} = dry base moisture (decimal fraction)

C_{DB} = dry base radionuclide concentration (pCi/g dry).

As one would expect, the dry base radionuclide concentration is larger than the wet base concentration because the activity is divided by the dry soil weight, which is less than the wet weight.

All *in situ* measurements need to be adjusted to take into account the soil moisture at or near the time of measurement. Two instruments are commonly used to measure soil moisture in the field: the Zeltex near-infrared reflectance moisture meter (Section 4.4.1) or the Dynamax dielectric sensing moisture meter (Section 4.4.2). A Troxler moisture-density gauge, which senses moisture content by the degree of thermalization of fast neutrons emitted from a source within the gauge, is also available for measuring soil moisture. The other moisture meters are preferred over the Troxler gauge because of the potential for interference with *in situ* gamma spectrometry measurements from radioactive sources in the Troxler gauge.

5.5.1 Guidance

- All *in situ* gamma spectrometry data should be displayed in maps or tables on a dry weight basis. Comparison to limits such as three times the FRL or WAC shall be made on a dry weight basis.

5.5.2 See Also

4.4 Field Moisture Measurements
4.12 Environmental Influences on *In situ* Gamma Spectrometry Data

5.6 RADIUM-226 CORRECTIONS

Ra-226 activity in soil is measured using gamma photons emitted by its radioactive daughters. Ra-226 is a member of the U-238 decay series. The relevant part of the U-238/Ra-226 decay series is:

$$^{226}Ra \rightarrow \alpha + {}^{222}Rn \rightarrow \alpha + {}^{218}Po \rightarrow \alpha + {}^{214}Pb \rightarrow \beta^{-} + {}^{214}Bi$$

Tables 2-3 and 2-4 show the gamma photons used to quantify Ra-226. NaI detectors cannot resolve the lead and bismuth gamma peaks below 1500 keV from other interfering peaks; therefore, NaI detectors measure the 1764.5 keV bismuth-214 peak to quantify Ra-226.

If the half life of a radioactive parent isotope is long compared to that of its daughters, after a relatively short time period, all members of the decay series will have equal activities. This is referred to as secular equilibrium. Under these conditions, a valid measurement of parent activity can be obtained by detecting the radiation emitted by one of the daughters. However, if some physical or chemical process causes the parent and daughter to become spatially separated, the conditions for maintenance of secular equilibrium are no longer valid, and one can no longer be assured that parent and daughter isotopes will have equal activities. Unfortunately, this is the case for Ra-226. Because radon-222 (Rn-222), the first daughter of Ra-226, is a gas that can build up or diffuse out of the soil, be transported as a dissolved gas in rainwater or groundwater, or be trapped in the layer of air just above the soil surface, it is generally not valid to assume secular equilibrium between Ra-226 and its daughters below Rn-222 in the decay series. When *in situ* measurements of Ra-226 are performed, it is common to obtain results based on emissions from daughters below Rn-222 that are 30% to 40% lower than results based on direct emissions from Ra-226.

In order to use gamma rays from Pb-214 and Bi-214 to quantify Ra-226 in the soil, two separate corrections must be applied to the *in situ* measurement results, both of which are at least partially related to the disruption of the equilibrium between Ra-226 and its daughters below radon in the decay series.

First of all, as noted in the 1999 Comparability Study (DOE 1999a), a correction must be applied to *in situ* radium measurements to compensate for the fact that the *in situ* results are biased low relative to laboratory analyses of soil samples for Ra-226. Second, it was also noted in the 1999 Comparability Study that *in situ* radium measurement results at a single location varied throughout the day due to the degree to which radon has emanated from the soil into the atmosphere. The first of theses corrections is referred to as the lab-field correction and the second is known as the time-of-day correction. These corrections will be discussed further as they apply to HPGe and NaI measurements.

5.6.1 Time-of-Day Corrections for Ra-226 Measurements

Table 3 and Figure 6C in the report "Effect of Environmental Variables Upon *In Situ* Gamma Spectrometry Data" (DOE 1997) indicate that morning Ra-226 measurements at a given location can average 30 percent higher and have a larger standard deviation than afternoon measurements. The considerable variability of morning Ra-226 measurements is attributed to changes in atmospheric and soil conditions due primarily to the heating effect of the sun. Atmospheric mixing, induced by solar heating, can drastically alter radon concentrations in the lower atmosphere and in surface soil. Correction of morning HPGe Ra-226 measurements to account for variation in the Rn-222 emanation is necessary in certain situations, such as when uncorrected measurement results slightly exceed the 3xFRL hotspot criterion. This Time-of-Day correction, which requires the use of a radon monitor, is described below. While sodium iodide detectors have the sensitivity needed to support Ra-226 hot spot decisions, areas scanned by NaI systems can sometimes be quite large, requiring multiple radon monitors to accurately reflect radon mixing conditions over the entire area. Consequently, radon monitors are generally not deployed in conjunction with NaI scans. The guidance below applies only to *in situ* HPGe measurements of Ra-226.

Table 5-3 shows a sample data set of HPGe Ra-226 readings collected on January 31, 1998 in the East Field of the FCP [Area I Phase II (AIPII)]. These 15-minute measurements will be used to illustrate the Time-of-Day correction process. A radon monitor was deployed nearby as these measurements were performed. Figure 5-2 is a graphical representation of the radon monitor readings associated with the AIPII data. This graph clearly shows that the radon monitor readings (Ra-226 pCi/g) at this location, gradually decreased throughout the day. So called "diurnal correction ratios" were computed by dividing each radon monitor reading by the lowest afternoon radon monitor reading. These diurnal correction ratios are listed in the third column of Table 5-3, and they are plotted in Figure 5-3 as a function of the time of day. To arrive at Ra-226 concentrations equivalent to what would have been measured if the readings had taken place in the afternoon, at the time of minimum Rn-222 buildup, **divide** the

in situ HPGe Ra-226 results by the diurnal correction ratio closest in time to the start of each spectral measurement. Software has been developed to automatically compute the diurnal correction ratios and to perform the Time-of-Day corrections. However, this type of correction cannot be initiated until both radon monitor and field data acquisition are complete. The Ra-226 field readings, corrected for Time-of-Day radon variations, are shown in column 4 of Table 5-3. For the sake of completeness, Table 5-3 also contains columns that show the results of applying two additional corrections to raw *in situ* Ra-226 results, the Lab-Field correction and the moisture correction. These corrections are discussed in other sections of this chapter. Three separate corrections must be applied before Ra-226 results are mapped or reported to remediation project personnel: Time-of-Day (also known as diurnal) corrections, Lab-Field corrections and moisture corrections. The right-most column of Table 5-3 shows fully corrected Ra-226 results that are suitable to be reported.

5.6.1.1 Guidance

- When appropriate, a "radon monitor" will be set up in the vicinity of the area in which HPGe measurements will be made. This radon monitor will make continuous 5-minute measurements at a fixed location for the entire afternoon during which any *in situ* Ra-226 data were acquired with HPGe systems.
- For large, relatively flat areas, the radon monitor should be within 400 m of the other HPGe measurements. For small, flat areas, the radon monitor should be within the perimeter of the area. For areas with significant differences in topographic elevations, such as deep pits, valleys and hills, consult the RTIMP group for guidance.
- The radon monitor detector height should be the same as the HPGe detector performing the field measurements.
- The process of correcting Ra-226 field readings for diurnal Rn-222 variations consists of calculating diurnal correction ratios from radon monitor data and then dividing each field reading by the applicable diurnal correction ratio. The diurnal correction ratio for the time period closest in time to the start of each individual spectral acquisition is the appropriate one to use.
- After correcting Ra-226 data for diurnal radon variations, apply Lab-Field corrections and moisture corrections to arrive at final corrected Ra-226 concentrations that are suitable for reporting.
- The above guidance will yield Ra-226 data that satisfy ASL B data quality requirements.

5.6.2 Lab-Field Correction of HPGe Measurements

Afternoon Ra-226 measurements represent steady-state dissipation of Rn-222 from soil, which leads to consistent values for measured Ra-226 activity. As noted above, afternoon *in situ* gamma spectrometry data are consistently lower than laboratory data. Further, these differences increase as the Ra-226 activity in the soil increases. To compensate for these differences, a correction algorithm, the Lab-Field

correction, was developed to adjust a field Ra-226 result to a value that would have been reported by a laboratory. As described in reference DOE 1999a, a series of *in situ* measurements were performed and a laboratory analyzed multiple samples collected from the same locations. Using regression techniques with these data, an equation was developed to predict what a laboratory would have reported if it had analyzed physical samples from the location of the *in situ* Ra-226 measurement. Two other methods of correcting radium data for radon daughter disequilibrium, which is a large component of the Lab-Field correction, were investigated after the publication of DOE 1999a. Because neither of these approaches was clearly superior to the current correction method and because they yielded corrected Ra-226 results similar to those from the currently approved regression equation presented below, it was decided to retain the current approach. The Lab-Field correction is applied to all *in situ* HPGe results before comparison to any applicable Ra-226 limits.

5.6.2.1 Guidance

- To standardize data reduction practices, first apply the Time-of-Day correction to "as is" or "wet weight" *in situ* Ra-226 results, then apply the Lab-Field correction, and lastly apply the moisture correction to arrive at a final dry weight result.
- The following equation represents the Lab-Field correction to be applied to all *in situ* HPGe Ra-226 results. The resultant corrected value represents the Ra-226 soil concentration that a laboratory would have reported.

$$Ra_{corr} = 0.34651 \times (Ra_{field})^2 + 0.98438 \times (Ra_{field})$$

where Ra_{field} = "as is" Ra-226 measurement result from the gamma spectrometer after the Time-of-Day correction has been applied (pCi/g wet),
Ra_{corr} = lab equivalent Ra-226 result, i.e., result corrected for the low bias present in *in situ* Ra-226 measurement results relative to what a laboratory would report (pCi/g wet).

- After applying the above correction, convert radon-corrected wet-weight measurements to dry-weight results as described in the section on moisture corrections (Section 5.4).

5.6.3 Lab-Field Correction of NaI Measurements

NaI data are routinely corrected to account for Rn-222 disequilibrium in soils using the Lab-Field correction. However, Time-of-Day corrections are not normally applied to NaI measurements because they are not used without confirmatory HPGe measurements to make 3*FRL hot spot decisions. The Lab-Field correction algorithm for NaI instruments was derived in the same manner as that for HPGe instruments. That is, NaI measurements were performed at a series of locations that contained Ra-226 in the soil. Multiple physical samples were collected from each of these locations and analyzed in a laboratory. Regression analyses were then performed with these two sets of measurements to derive an

equation that would predict what a laboratory would report if samples had been collected from the site of a NaI measurement. The empirically derived NaI Lab-Field correction algorithm given below has the same mathematical form as that derived for HPGe instruments, but the numerical values of the NaI coefficients are different from the corresponding HPGe coefficients. The difference between the HPGe and NaI coefficient values is attributed to the difference in photon detection efficiency and resolution of the two types of detectors.

5.6.3.1 Guidance

- Correct NaI Ra-226 measurements for the effects of radon disequilbrium in soil using the Lab-Field correction algorithm shown in the following equation:

$$Ra_{corr} = 0.46018 \times (Ra_{field})^2 + 0.551 \times (Ra_{field})$$

where

Ra_{field} = "as is" NaI Ra-226 measurement result (pCi/g wet),
Ra_{corr} = lab equivalent Ra-226 result, i.e., result corrected for the low bias present in *in situ* Ra-226 measurement results relative to what a laboratory would report (pCi/g wet).

- After performing the Lab-Field correction shown above, convert corrected wet weight measurements to dry weight measurements as described in the sections on moisture corrections (Section 5.5).
- Lab-Field corrected NaI Ra-226 data satisfies ASL A data quality requirements.

5.6.3.2 See Also

4.12 Environmental Influences on *In Situ* Gamma Spectrometry Data
4.15 Mapping Conventions
5.5 Moisture Corrected Data
5.7 Data Review and Validation

5.7 DATA REVIEW AND VALIDATION

Virtually all laboratories require an independent review of analytical data prior to reporting results to customers. Data review by an independent knowledgeable person is also a key element in the RTIMP program to ensure that *in situ* gamma spectrometry results are of the highest quality. During the RTIMP data review process key elements such as the following are evaluated: the quality of the spectral data, the successful completion of instrument performance checks, the parameters used in the computation of radionuclide concentrations, the proper application of correction factors, the need to flag data as suspect or unusable, the completeness of the records and transfer of approved results to the SED. The sections below describe the data review process and the checklists employed to assure consistency

and completeness in the review of HPGe and NaI data. A more comprehensive outline of the steps in the data review process appears in the RTIMP Operations Manual (RTIMP-M-003). Major elements of the RTIMP QA and QC programs are outlined in SCQ Appendix H (DOE 2002c).

5.7.1 RTIMP Internal Review of HPGe Data

The RTIMP has developed two checklists, one for HPGe data and one for NaI data, to aid in the review process and to document compliance with the detailed instructions in the RTIMP Operations Manual, M-003, regarding real-time data review. By going through the checklist item by item, the analyst is guided to assemble and review all the pertinent data associated with a set of *in situ* measurements. Table 5-4 contains a list of questions extracted from the HPGe Data Verification Checklist, form number FS-F-5509, that are pertinent to an evaluation of the completeness and technical adequacy of a set of HPGe measurements. Note that the data review involves not only a determination of whether or not the spectral data appear to be free of interferences and other anomalies, but also verification that required QC measurements were acceptable. After an analyst completes the initial review, another knowledgeable individual reviews the checklist, the results and the associated hard-copy documentation for accuracy and completeness. All *in situ* data collected in support of remediation activities undergo this independent review. Measurement results can be issued to customers only after the analyst and a second party reviews the raw data. A separate data verification checklist is completed for each HPGe detector used on a given day.

The specific responsibilities of the RTIMP group, regarding HPGe data verification, include verifying:

- PSP measurement requirements have been met,
- HPGe detectors have current calibrations,
- QC checks have been performed and acceptance criteria have been met,
- Required documents have been completed,
- HPGe measurements have been verified (checklist FS-F-5509), based on a review of logs, raw spectra, and results,
- Data have been loaded into appropriate LAN and SED directories,

5.7.2 External Validation of HPGe Data

Depending on the intended use of the data, remediation projects may elect to have *in situ* measurement results validated by a group completely independent of the RTIMP. This function is performed by the Data Quality Section of the Quality Assurance Programs Department within the Safety, Health and Quality Division of Fluor Fernald. When independent data validation is needed, personnel from the

Data Quality Section can access RTIMP hard-copy records such as field worksheets and detector control charts, as well as electronic records such as spectral data files and results posted to the SED. Checklist FS-F-5614, *In Situ* HPGe Gamma Spectrometry ASL B Data Validation Checklist, has been developed by the Data Quality Section to carry out and document the formal data validation process. The HPGe data validation process is similar to that used for other types of analytical data. Its purpose is to confirm that HPGe data were properly acquired and properly documented and loaded into the SED, that all required QC measurements associated with the data satisfied performance specifications, and that all measurements specified in the PSP were performed. Based on the results of their independent review, data validators may assign standard qualifiers to the *in situ* results in the SED, just as they do with data generated by an analytical laboratory.

5.7.3 RTIMP Internal Review of NaI Data

The analyst who generated it, and another knowledgeable individual within the program, review all RTIMP NaI data before the results are released to customers. The RTIMP has developed an NaI Data Verification Checklist (form number FS-F-5508) specifically to document the review of mobile sodium iodide measurements. Items in the checklist correspond to the NaI data review instructions in the RTIMP Operations Manual. Table 5-5, a reproduction of the NaI Data Verification Checklist, shows the questions that are pertinent to an evaluation of the technical accuracy of this type of data. Because these data are acquired in a mobile scanning mode, the adequacy of GPS information must be evaluated in addition to the quality of the spectral data and the acceptability of the instrument QC checks. As is true of HPGe data, after an analyst completes an initial review, another knowledgeable individual reviews the checklist, the results and the associated hard-copy documentation for accuracy and completeness.

One aspect of data review is the examination of spectra. However, because the NaI systems could collect as many as 900 spectra per hour at a 4-second data acquisition time, the analyst and the independent reviewer rely heavily on data quality checks built into the LabView software which controls data acquisition and analysis. The software monitors data quality indicating parameters such as MCA gain and offset, dead time and net count rates for the isotopes of concern, and writes error flags to a log file when any of these parameters are outside specified limits. Generally individual spectra are examined for anomalies only when error flags appear in the log file. One NaI checklist is completed for each NaI data set collected as a single batch file. A batch file is generated for each area and function (e.g. lift number) being scanned. For example, if two NaI systems scanned two lifts each, in two separate areas, four batch files would be generated.

The specific responsibilities of the RTIMP group, regarding NaI data verification, include verifying:

- PSP measurement requirements have been met,
- NaI detectors have current calibrations,
- QC checks have been performed and acceptance criteria have been met,
- Required documents have been completed,
- NaI measurements have been verified (checklist FS-F-5508), based on a review of logs, raw spectra (if necessary), and results,
- Data have been loaded into appropriate LAN and SED directories,

5.7.4 External Validation of NaI Data

Mobile sodium iodide data are generally considered to be ASL A data. There is no reason, in principle, why these data could not be validated by someone independent of the RTIMP. However, formal external validation of these data is not usually requested.

5.7.5 Guidance

- Data verification by RTIMP personnel is required for all HPGe and NaI data acquired in support of remediation activities.
- Data verification is documented by completing Checklist FS-F-5508 for NaI data or Checklist FS-F-5509 for HPGe data.
- HPGe measurements are typically considered to be ASL B measurements, whereas mobile NaI measurements are classified as ASL A measurements.
- It is the responsibility of individual remediation project managers to decide when formal validation of data generated for their project will be requested. The data validation function is performed by the Data Quality Section of the Quality Assurance Programs Department.
- Independent data validation is a formal process for reviewing the records associated with a set of measurement results to assess the technical accuracy of the measurements and the documentation demonstrating that the analytical systems were functioning properly and within their normal limits. Data validation addresses data completeness, documentation, storage, and quality as indicated by QC measurement results.
- If no qualifiers are attached to the data in the SED database, the data are usable without restriction for their intended purpose.
- As a result of the data validation process, the Data Quality Section may add qualifiers to *in situ* data stored in the SED. Data are "qualified" in two ways in the database. An "R" qualifier means that data are rejected and must not be used. An "S" qualifier means that even though one or more QC or data review elements have not been met, the data are usable for their intended purpose, but are still considered "suspect." Suspect means that the data values are approximations of the true concentrations of the analytes in the soil. Suspect data must be reviewed before being used for any other purpose than originally intended.

- Locations corresponding to rejected *in situ* data should be measured again, if possible, as appropriate.
- Individual NaI measurements may be rejected as unusable without rejecting the entire NaI batch.

5.7.6 See Also

2.1 HPGe Systems and Measurements
2.2 RTRAK System and Measurements
2.3 RSS Systems and Measurements
2.4 Gator System and Measurements
2.5 EMS and Measurements
4.11 Surface Condition and Topographic Effects
4.13 Shine and Buried Sources
5.5 Moisture Corrections
5.6 Radium-226 Corrections

5.8 CONTAMINANT HETEROGENEITY

Contaminant heterogeneity can exist on the soil surface and with depth below the surface. At the FCP, the size of a heterogeneous spot can vary across a wide range from a centimeter or less (e.g., particles), to meters (e.g., dumping or localized spills), and even to tens or hundreds of meters (e.g., airborne sources). No single measurement technique can be expected to average all potential variations, and a given size area can be homogeneous for one radionuclide but heterogeneous for another. Thus, measurement approaches must incorporate appropriate measurement density to ensure that characterization goals are achieved. Proper characterization of an area must give due consideration to the possible scale of heterogeneously distributed contaminants.

Definitions regarding the degree of heterogeneity applicable to remedial work at the FCP are as follows:

Low Heterogeneous Areas	Radionuclide concentrations range over a factor of 2 or less over an area the size of a certification unit, for example. Low heterogeneous areas are most likely to be uniformly below FRLs.
Medium Heterogeneous Areas	Radionuclide concentrations range over a factor of 2 to 5 over an area similar to an HPGe field of view, for example (about 100 m^2). Medium heterogeneity areas might contain low-level hot spots.
High Heterogeneous Areas	Radionuclide concentrations range over a factor of 5 or more over an area similar to a NaI field of view, for example (about 20 m^2). High heterogeneous areas might contain WAC exceedances or hotspots.

The degree of contaminant heterogeneity will be assessed both before and after remedial operations. Before remediation operations in a given area, the degree of heterogeneity will be estimated based upon RI/FS data and process knowledge. After remediation operations in a given area, the degree of heterogeneity can be assessed based upon *in situ* gamma spectrometry data as well as any data obtained from physical samples.

The scale of heterogeneity can be related to detectability with the HPGe, NaI, and hand-held survey meters.

- Medium and high heterogeneities with < 0.5 m radius may be detected with hand-held survey meters, by HPGe at a 15 cm detector height, and by NaI systems.
- Medium and high heterogeneities having a 0.5 to 2.0 m radius can be detected by NaI systems and by HPGe at either 15 cm or 31 cm detector height, depending upon the radionuclide concentrations.
- Low, medium and high heterogeneities having a 2.0 m to 4.0 m radius can be detected by NaI systems and by HPGe detectors at either 31 cm or 1.0 m detector height, depending upon the range of radionuclide concentrations.
- Low, medium or high heterogeneities with a radius greater than 4.0 can be detected by HPGe at 1.0 m detector height and by NaI systems.

The interplay between contaminant concentration, scale of heterogeneity and equipment recommendations is summarized in Tables 5-6 through 5-8. For example, in a medium heterogeneous area with a 0.5 to 2.0 m radius hot spot (1 to 12 m^2 area), HPGe measurements at a 15 cm detector height are the recommended approach (Table 5-7). With a field of view of about 3 m^2, adjacent measurements could detect concentration differences over a hot spot area of this size that might be washed out in an HPGe measurement at a 31- centimeter or a one-meter detector height. As noted in Table 5-6, small areas of low heterogeneity are not of particular concern in remediation.

Because NaI systems are used for most of the initial coverage of an area, NaI is the primary tool for recognizing heterogeneous areas. Using the results from NaI surveys, HPGe measurements are then focused on specific areas that were indicated by NaI measurements as potential hot spots or WAC exceedances.

5.8.1 Guidance

- For protocols on how to detect, confirm, and delineate hot spots in heterogeneous areas, as well as to interpret data from such measurements, refer to Sections 3.3.1 (Hot spot Evaluation).
- For protocols on how to detect, confirm, and delineate WAC exceedances in very heterogeneous areas, as well as how to interpret data from such measurements, refer to Section 3.1.3 (Above-WAC Detection, Confirmation and Delineation), Section 4.9 (Detection of Above-WAC Uranium Contamination) and Section 4.8 (Trigger Levels).
- For guidance on how to present and interpret NaI data, refer to Section 4.15 (Mapping Conventions) and Section 4.14 (Interpretation of NaI Total Activity Data).
- Refer to Tables 5-6 through 5-8 for guidance and information as to instrument type and detector height for various measurement objectives in heterogeneous areas.

5.8.2 See Also

3.3.1 Hot Spot Evaluation
3.1.3 Above-WAC Detection, Confirmation, and Delineation
4.5 Detector Field of View and Area Coverage
4.8 Trigger Levels
4.9 Detection of Above-WAC Uranium Contamination
4.10 Use of Hand-Held Survey Meters
4.14 Interpretation of Total Activity Data
4.15 Mapping Conventions

5.9 QUALITY CONTROL CONSIDERATIONS FOR FIELD MEASUREMENTS

The RTIMP QAP (20300-PL-0002) and RTIMP Operations Manual (RTIMP-M-003) have been written to govern the quality control program for *in situ* gamma spectrometry measurements. Although RTIMP-M-003 primarily addresses traditional QC elements such as accuracy, precision, use of control charts, etc., it also specifies a number of daily equipment checks that must be performed to document instrument response over time, which helps to ensure measurement integrity. For example, on a periodic basis, and especially when working in high dirt/dust areas, the cable connectors and terminals should be cleaned to ensure good connection and thus, proper operation. General guidance regarding instrumentation problems that may adversely effect the quality of the data is summarized below.

5.9.1 Guidance

Field Use of HPGe

- If High Voltage LED is not illuminated, check the following:
  - Ensure power switch is on
  - Ensure low battery LED is not illuminated. Note: If low battery light is illuminated, there will probably not be enough power to operate the multichannel analyzer.
  - Ensure battery is properly installed in the multichannel analyzer.

- If the gamma spectroscopy software indicates "can't read MCB" or it won't switch over from the buffer to the detector, check the following:
  - Ensure 9-pin preamp cable and BNC connectors are properly connected to the multichannel analyzer
  - Ensure 25-pin parallel printer port cable is securely connected
  - Ensure all cables are connected to the appropriate terminals and properly seated.
- If detector voltage cannot be enabled, check the following:
  - Ensure bias shutdown cable is securely connected to the proper terminal (i.e., SD)
  - Ensure the voltage applied to the detector matches the manufacturer's recommended voltage.
  - Ensure detector is properly cooled (i.e., filled with liquid nitrogen)
- During energy calibration if RESOLUTION or NET PEAK AREA are not within QC limits, check the following;
  - Ensure detector and check source are in proper fixed geometry.
  - Ensure no foreign (shielding) objects are between source and detector.
  - Ensure no other radiological sources are in the area
- When performing field measurements, if the RESOLUTION of K-40 peak is too high (i.e., greater than 3 keV FWHM), check the following:
  - Are there sources of electromagnetic/radio frequency interference?
  - Is there interference from other radiological sources?
  - Is there interference from isotopes with energy close to that of K-40 (Th-230, Th-232)?
  - Do the detector control charts show a trend toward increasing resolution, which can be an indication of gradual detector failure?

Field Use of the NaI systems

- Sodium iodide systems should not be driven in/on the following areas:
  - Steep inclines
  - Across ditches or into deep pits where the detector could be damaged by striking the ground
  - Through standing water
- Take proper precautions when traveling and crossing roadways
- Be especially cautious when scanning near low lying tree branches or under a tree canopy because GPS signals could get blocked or the GPS antenna could get snagged on limbs
- Ensure energy calibration sources (i.e., thorium mantles) are removed from the detector and placed in the designated storage area after performing instrument response checks.
- Use caution when working around the RTRAK because tire punctures can result in personnel being sprayed with calcium chloride, which is the fill material in the RTRAK tires.

- Jarring and bumping of instrumentation may cause the spectrometer gain (i.e., the energy calibration) to shift and render data unusable
- When using the NIM bin-type multichannel analyzer in the RTRAK cab, monitor the temperature inside the cab as temperature changes may cause spectrometer gain drifts.
- When starting on-board generator in the RTRAK, use the manual choke if it does not start up right away

General Considerations:

- Radioactive calibration sources and other sources of radiation, if possible, should be moved at least 75 m from NaI or HPGe systems during field measurements.
- Personnel must avoid standing in or placing objects within the detector field of view while measurements are in progress.
- To the extent possible, field of view obstructions should be removed or minimized.
- When performing *in situ* measurements, an attempt should be made to keep measurement dead time less than 40 percent. Data acquired with dead times greater than 20% should be examined carefully to determine if the elevated dead time has adversely effected the data.
- The general shape of a gamma ray spectrum can provide the general indication of the quality of the data. The spectrum continuum should be generally smooth with no abrupt shifts, or broad humps in between spectral peaks.
- The shape of spectral peaks can also be a general indicator of the quality of spectral data. There should be no low energy or high energy tailing on the sides of peaks. Peaks should not be unusually broad or too narrow.

5.9.2 See Also

4.11 Surface Condition and Topographic Effects
5.7 Data Review and Validation

5.10 POSITIONING AND SURVEYING

Static and dynamic position measurement techniques are required to identify the geographic locations of the HPGe and NaI measurements. Exact determination of these measurement locations is crucial to the production of accurate maps which in turn leads to proper characterization and remediation. Field coordinates for HPGe readings are easily determined using conventional survey methods and equipment (total stations, electronic theodolites, or GPS) to stake out locations or grid points. The physical locations of mobile NaI system measurements are determined by readouts of satellite telemetry information processed by differential global positioning systems (DGPS).

5.10.1 HPGe Systems

Both HPGe and NaI measurements require the same degree of accuracy. However, because *in situ* HPGe measurements are generally performed in a stationary mode, a variety of options are available for determining HPGe measurement locations. In addition to GPS techniques, these include conventional and electronic survey tools, and laser range finder systems. There is also no time constraint on the position measurements. That is, locations for HPGe measurements may be marked and the radioactivity measurements may be performed independent of when or how the exact positions of these locations are determined. The location measurements could be performed before, during or after the HPGe measurements, as long as precautions were taken to ensure the location markers were not disturbed. HPGe measurement locations are recorded on field worksheets and become part of the header string in electronic spectral files so that radionuclide concentrations determined from a particular *in situ* measurement may be tied to the location of the measurement.

5.10.2 NaI Systems

The FCP selected a GPS receiver as the primary positioning system for the NaI systems, because of the receiver's ability to achieve sub-meter positioning accuracies and the versatility of the receiver to interface or "speak" with external electronic devices. The receiver incorporates the GPS and DGPS signal processing circuitry into a single unit, thus eliminating the need to interface two separate receivers. The GPS "engine" consists of a 12-channel, parallel tracking receiver with a latency update frequency of one hertz. A single antenna integrates the GPS and the differential correction signal, thereby providing the user with an instantaneous corrected position. The system is compatible with a variety of external electronic sensors, including lasers, rangefinders and dataloggers, making it ideal for various mapping applications. These receivers can provide position measurements with a horizontal error as low as 15 cm and vertical errors as low as 30 cm. Under ideal conditions, measurement accuracy is better than ± 10 cm.

5.10.3 Factors Affecting GPS Positioning

The NAVSTAR global positioning system is highly reliable and provides consistent operation when used properly. Although the occurrence of errors during GPS positioning is uncommon, users must be familiar with factors and limitations that can adversely impact positioning data. GPS satellites are operated and controlled by the U.S. Department of Defense, and adjustments to the integration of signals with the atomic clocks can provide erroneous signal information if updates are not accounted for.

Although the GPS is available 24 hours a day, certain time periods exhibit optimal satellite telemetry and availability (information is obtained from support services on the internet). Mission planning software is used to monitor optimal time frames for conducting GPS operations and to identify periods of the day that may not yield satisfactory results. Also, resources are available that indicate periods of poor satellite health. Resources include various web pages, typically provided by government institutions, including the Coast Guard, U.S. Navy, several gas manufacturers, and some universities with advanced mapping programs. Knowing this, the user can "turn off" any signals that may be received from the unhealthy satellite.

Dense tree canopies or tall structures may be responsible for blocking GPS signals, geostationary differential correction signals, or for producing a multipath error caused by a bounced, i.e., reflected, signal. Multipath error occurs when satellite signals are reflected from nearby objects such as trees, fences, vehicles, buildings, and water surfaces. Modern receivers use advanced signal processing techniques to minimize the problem, but in some severe cases it can add some uncertainty to the location of a GPS measurement. Field experience with the use of GPS equipment will educate the user as to degrees of latitude for antenna placement when working around obstructions that may interfere (block or bounce) with the GPS radio signals.

The application of GPS technology provides a cost effective and dependable method of positioning anywhere on or above the earth's surface. Proper use of the positioning equipment and an awareness of its operational limitations will yield accurate location measurements. Familiarity with the prospective work site and prior satellite mission planning will significantly reduce, if not eliminate, possible GPS positioning errors.

5.10.4 Guidance

- Planning software and almanacs should be used to determine optimal periods in a given day for conducting *in situ* measurements requiring GPS operations. The objective is to avoid running NaI at times of poor signal reception.
- The FCP considers GPS signals associated with PDOP values less than or equal to 6 to be acceptable for use.
- If possible, avoid performing *in situ* measurements where GPS signals will be blocked or in locations which could lead to multipath error effects. Multipath errors cannot be corrected for in the field. Through use and experience, the user should become familiar with the types of features that cause multipath to occur and learn to avoid those obstacles to the extent possible. Familiarity with the prospective work site and prior satellite mission planning will significantly reduce, if not eliminate, possible GPS positioning errors and allow proper focus toward radionuclide detection errors.

- GPS quality indicators (0, 1, 2) sent from the GPS receiver indicate the quality of the GPS signal being recorded. Zero indicates an invalid GPS fix (loss of GPS signal); a "1" indicates a GPS fix (GPS signal received with loss of the differential correction); and a "2" represents a differential GPS fix. By reviewing these data records, the analyst can determine positioning errors resulting from satellite signal loss or blockage. Additionally, when plotted on site reference maps, it is possible for the analyst to determine the source or factor that may have contributed to signal loss.

5.10.5 See Also

4.11 Surface Condition and Topographic Effects
4.15 Mapping Conventions
5.8 Quality Control Considerations for Field Measurements

5.11 ANALYSIS OF UNCERTAINTIES IN HPGe AND NaI MEASUREMENTS

In accordance with recommendations in the MARSSIM manual (NRC 2000), the RTIMP reports measurement uncertainties along with results of radionuclide concentration in the soil for all *in situ* measurements. This includes both HPGe and NaI data. For a variety of reasons related to differences in the fundamental properties of the detector materials, the calibration methodologies and the modes of operation, the uncertainty analyses for HPGe and NaI measurements are each approached in a unique manner. They will be discussed separately in the next two sections of this manual.

5.11.1 HPGe Measurements

For typical measurement situations encountered at the FCP, counting statistics are better for HPGe than for NaI measurements. This is due to the longer count time used in HPGe measurements. The superior resolution of HPGe detectors and better counting statistics enables the RTIMP to use full-featured gamma spectral analysis software to locate spectral peaks, determine the centroid location and base widths of peaks, determine background counts and net counts for each spectral peak, and calculate radionuclide concentrations. In the latter calculation, the software identifies the isotopes causing the spectral peaks by comparing peak centroid energies to a list of characteristic energies associated with known gamma-emitting isotopes stored in the MCA memory and uses specific properties of the identified isotopes to compute their activity. All of these tasks can be performed automatically, without intervention by the operator.

Since radioactive decay is a random process, repeatedly counting the emissions from a given source will not yield the same value each time. After repeating the count a large number of times, Poisson statistics can be used to predict the most probable count and how widely spread out the individual count values are likely to be. In other words, we can estimate the "true" count and attach some uncertainty to this

estimated value. This is referred to as "counting uncertainty" or, more commonly, "counting error," although there is no real error, in the sense of a mistake, associated with the count. In addition to reporting radionuclide concentrations, the gamma spectral analysis software used by the RTIMP also reports the associated uncertainty. The topic of counting uncertainty has been treated extensively in the scientific literature, and will not be presented in any detail here. The key variable associated with an *in situ* radioactivity measurement is the net peak count rate, which is determined by subtracting the gross peak counts in a region of interest from the background counts, and dividing this difference by the count time. Thus the uncertainty in the net peak counts requires knowledge of the uncertainties in the gross and background counts. Standard error propagation formulas may be used to compute the resultant uncertainty in the net counts. Applying the same conversion factors that were used to derive the radionuclide concentration from the net peak count rate, one can calculate the associated uncertainty in the measured concentration. The computations become somewhat more complex if there are other gamma rays that interfere with the one of interest or if a particular nuclide emits more than one gamma ray. However, the general principle of deriving the uncertainty in a measured radionuclide concentration from the uncertainty in the associated net count rate still holds. The uncertainty in HPGe measurement results reported by the RTIMP is the counting uncertainty calculated by the gamma spectrometry software in use at Fernald for *in situ* measurements. This is common practice in the field of *in situ* gamma spectrometry measurements. It is recognized that there are other components in the overall HPGe measurement uncertainty that have not been thoroughly evaluated. However, ample data has been provided in the January 1999 Comparability study to demonstrate the comparability of *in situ* HPGe measurements and laboratory analysis of physical samples. This is true for afternoon measurements of Ra-226 after the Lab-Field correction has been applied, as well as for total uranium and Th-232. Given the agreement between lab and *in situ* measurements, there is little to be gained by an extensive study of the magnitude of the other sources contributing to the overall uncertainty of HPGe measurements.

5.11.2 NaI Measurements

Uncertainties in NaI measurements were analyzed in detail in the report entitled "Measurement Uncertainties and Minimum Detectable Concentrations for the *In Situ* NaI Gamma Spectroscopy Systems Used at the Fernald Site (ANL 2004). This analysis reviewed the measurement process and identified sources of uncertainty. The variances of individual inputs contributing to the final measurement were estimated by appropriate means. It was crucial to the validity of the uncertainty analysis that all facets of the measurement and data reduction process, including the recent improvements in the NaI data analysis software (gain tracking and determination of peak backgrounds by spectral sanding) be duly considered in

the uncertainty analysis. Using standard "propagation of error" techniques, the input variances were then combined mathematically to yield estimates of total uncertainty in the final measurement outputs, radionuclide activity concentrations in soil. The following is a synopsis of the methods and results presented in the report.

The measurement process used to determine soil concentrations of U-238, Ra-226, and Th-232 using the NaI systems involves the following steps:

- Total counts in the region of interest (ROI) of the gamma ray of interest for each isotope for the counting period, usually 4 seconds, are determined.
- Background counts for each spectral ROI are determined by a technique called spectral sanding.
- The net count rate is determined as the difference between the total counts and estimated background counts in the ROI divided by the count time.
- Net count rates are used in calibration equations to convert count rate to wet-weight soil concentrations for each radionuclide.
- For Ra-226, the Lab-Field correction is applied to the wet-weight concentration to account for radon loss from soil.
- Finally, soil moisture content as determined by a measurement in the field is used to convert wet-weight to dry-weight concentrations.

The following sources of uncertainty associated with the various measurement steps were considered in the analysis:

- Uncertainty in net count rates in the ROI for U-238, Ra-226, and Th-232.
- Uncertainty associated with calibration of the NaI detector systems.
- Uncertainty associated with the calibration sources and the calibration pad.
- Uncertainty associated with the vertical distribution of the radionuclides in soil (horizontal uncertainties were not considered).
- Uncertainty associated with the use of an empirical correction to account for radon loss from soil (the Lab-Field correction; the correction for morning radon buildup is not considered in this analysis).
- Uncertainty associated with the soil moisture measurement and conversion of wet-weight to dry-weight values.

The approach used to estimate NaI uncertainties is consistent with that endorsed by the American National Standards Institute (ANSI) and by the International Organization for Standardization (ISO) for the estimation of measurement uncertainties. In this approach, the uncertainty of the measurement output value is the positive square root (the standard deviation) of the combined variance of the input values

used to determine the output value. The analysis accounts for any covariance of input values. In the current analysis, all inputs were determined to be independent (zero covariance), except for the calibration coefficients in the calibration equation.

As discussed in Section 5.6.3 of this report, Ra-226 is unique among the isotopes of concern at the FCP, in that it is inappropriate to assume it to be in equilibrium with the daughter isotopes that emit the gamma rays used to quantify it. This necessitates the application of two separate correction factors (Lab-Field corrections and Time-of-Day corrections) to wet-weight Ra-226 measurements to compensate for radon loss from the soil. The uncertainties associated with these two correction algorithms are not quantitatively evaluated in the uncertainty analysis presented in reference ANL 2004. It is noted, however, that these could be substantial. It is also pointed out that even if the Lab-Field correction algorithm had no uncertainty, it has the potential to significantly magnify Ra-226 measurement uncertainties, because the algorithm involves the square of the uncorrected Ra-226 concentration. As an example, using data for the EMS system from Table A.2 of Reference ANL 2004, assuming a soil moisture content of 26%, an uncorrected wet-weight Ra-226 concentration of 2.4 pCi/g would give a radon corrected dry-weight concentration of 5.1 pCi/g, the limiting concentration for a radium hot spot. Before applying the Lab-Field radon correction, the measurement uncertainty (i.e. the relative standard deviation of the wet-weight result) would be ± 0.215. (This value 0.215 is computed as the square root of the sum of squares of the individual relative standard deviation terms in columns 2, 3, 4 and 5 of Table A.2 of reference ANL 2004.) However, the relative measurement uncertainty associated with the radon corrected wet weight result is ± 0.359. In this instance, even though it was assumed that there was no uncertainty in the Lab-Field radon correction process, the uncertainty in the radon corrected wet-weight result increased by a factor of 1.67. The Ra-226 measurement uncertainty would be affected even more at higher concentrations.

Results of uncertainty estimates for the various NaI platforms are presented in Table 5-9 for 4-second counts. In the calculation of the measurement uncertainty for one of the three radionuclides at a particular soil concentration, such as at the 3xFRL hotspot criterion, it was necessary to assume a soil concentration for each of the other two. For this purpose, it was arbitrarily assumed that U-238, Ra-226 and Th-232 were present at concentrations of 2.0, 0.5 and 0.5 pCi/g respectively, when they were not the radionuclide of interest. These are the background concentrations of these radionuclides in the RTIMP calibration pad, and they are somewhat above typical background levels for these isotopes in FCP soil.

As can be seen in Table 5-9, the measurement uncertainty, expressed as the standard deviation of the dry-weight concentration, varies little between the various NaI platforms. In general, at the three-times FRL level, estimated uncertainty in the dry weight concentrations is about 30% for U-238, 20% for Th-232, and 40% for Ra-226. At uranium WAC levels, uncertainty is about 20% for a 4-second measurement.

An examination of the sources contributing to the overall measurement uncertainty showed that for U-238, the major source of uncertainty for measurements at the three-times FRL level was counting error, about 50% of the overall uncertainty. Uncertainties associated with the vertical distribution of uranium in soil, the calibration pad, and the calibration process contributed about 20%, 15% and 10% respectively. For Th-232, the single largest source of uncertainty at 3*FRL was that associated with the vertical distribution of thorium in soil, about 45% of the overall uncertainty. For Ra-226 measurements at 3*FRL, the major sources of uncertainty are the vertical distribution of the radionuclide, the counting error and the calibration pad uncertainty. However these uncertainties are multiplied by a factor associated with the Lab-Field radon correction process. At the 3*FRL level, the radon correction process is estimated to contribute about 65% of the overall uncertainty.

Increasing the measurement time will reduce the counting error. Normally, if 4-second measurements are combined to obtain 8-second measurements, the counting uncertainty will decrease by a factor of about the square root of 2. However, such simple scaling cannot be applied to FCP NaI measurements because of the manner in which spectra are aggregated in the spectral sanding process and also because of the nature of the approximations used to estimate counting uncertainties.

The combined overall measurement uncertainty was found to be insensitive to the soil moisture level over the range of possible soil moisture values. Only the counting error is influenced by the moisture level, and its influence is not significant. For Ra-226 and Th-232, the relative counting uncertainty calculated for a moisture level of 26% is within 7% of the values obtained for moistures of 10% and 40%. For U-238, the corresponding difference is less than about 9%. The influence on the combined relative uncertainty is considerably smaller. The overall combined measurement uncertainty changes by no more than 8% as the soil moisture level is varied between 10 and 40%.

5.11.3 Guidance

- Total NaI measurement uncertainty is estimated by mathematically combining the variances of major contributing inputs, namely, net count rate, calibration process, calibration pad and sources, and vertical distribution of radionuclide in soil.
- Confidence in the estimates of the magnitude of uncertainty in the various contributing sources varies considerably. However, conservative estimates of uncertainty were used in all cases.
- Although the uncertainty in the radon correction process itself has not been evaluated quantitatively, it has the effect of magnifying the other sources of uncertainty.
- Uncertainty due to diurnal variation in atmospheric levels of Rn-222 daughters also increases measurement uncertainty in Ra-226 concentration. While the magnitude of this source of uncertainty has not been estimated, it can be minimized by performing measurements in the afternoon when atmospheric Rn-222 levels are lowest.
- Uncertainty estimates (relative standard deviations) vary little between NaI platforms. At the three-times FRL level, estimated uncertainty in the dry weight concentrations is about 30% for U-238, 20% for Th-232, and 40% for Ra-226. At uranium WAC levels, uncertainty is about 20%.
- At the three-times FRL level, the major contributor to NaI measurement uncertainty for U-238 is counting error (about 50%), for Th-232 is vertical distribution of thorium in soil (about 45%), and for Ra-226 is the Lab-Field (soil radon loss) correction process (about 65%).
- Although one might expect from first principles that relative measurement uncertainty will be reduced by a factor of about 1.4 (the square root of 2) when measurement time is increased by a factor of 2, this is not generally true for the NaI platforms because of the spectral sanding process used to determine peak backgrounds.

TABLE 5-1
HPGe MINIMUM DETECTABLE CONCENTRATIONS COMPARED TO FRLs

Analyte	FRL[a, c]	MDC[b, c] 5 Minute Count	MDC[b, c] 15 Minute Count
Total Uranium	82, 50, 20 or 10 mg/kg	8.3	4.8
Th-232	1.5 or 1.4 pCi/g	0.14	0.81
Ra-226	1.7 or 1.5 pCi/g	0.13	0.075

[a]Values of 50 mg/kg (Total U), 1.4 pCi/g (Th-232) and 1.5 pCi/g (Ra-226) represent offsite FRLs.
[b]MDCs vary somewhat from detector to detector. The table contains the maximum MDC value for typical measurement conditions, for each isotope, regardless of which detector it applies to.
[c]Analyte MDCs and regulatory limits are specified on a dry weight basis.

TABLE 5-2
NaI MINIMUM DETECTABLE CONCENTRATIONS COMPARED TO FRLs AND HOT SPOT CRITERIA
4-second Counts

Analyte*	FRL	Hot Spot 3*FRL	RTRAK MDC	RSS1 MDC	RSS2 MDC	RSS3 MDC	GATOR MDC	EMS MDC
Total U mg/kg	82	246	115	73	91	97	122	104
Th-232 pCi/g	1.5	4.5	0.8	0.7	0.7	0.7	0.8	0.8
Ra-226 pCi/g	1.7	5.1	2.0	1.4	1.5	1.5	2.0	1.7

* Analyte MDCs and regulatory limits are specified on a dry weight basis.

TABLE 5-3
HPGe RA-226 MEASUREMENTS CORRECTED FOR RADON DISEQUILIBRIUM

Time of Day (minutes corrected to fractional hours)	A1PII Radium-226 (pCi/g)	Diurnal Correction Ratio*	Time-of-Day Corrected Radium-226 (pCi/g)**	Lab-Field Corrected Radium-226 Result (pCi/g WET)	Final Corrected Radium-226 Result (pCi/g DRY)
8.52	0.84	1.39	0.61	0.87	1.16
8.78	0.79	1.43	0.55	0.77	1.04
9.05	0.78	1.42	0.55	0.77	0.99
9.24	0.75	1.42	0.53	0.74	1.01
9.55	0.71	1.33	0.53	0.75	1.10
9.91	0.79	1.26	0.63	0.91	1.32
10.03	0.82	1.30	0.63	0.91	1.14
10.28	0.76	1.32	0.58	0.82	1.08
10.34	0.71	1.32	0.54	0.75	1.01
10.53	0.63	1.20	0.52	0.73	0.90

* Taken from Figure 5-2.
** Equals values in Column 2 divided by values in Column 3.

TABLE 5-4
HPGe DATA VERFICATION CHECKLIST

Project No.:					
Project Name:					
Detector No:					
Completed By/Badge:			**Data Date:** **Date:**		
Location	**File-Run No.**	**Qualifier**	**Location**	**File-Run No.**	**Qualifier**
Data copied to RTIMP/Labview folder:					
Copied By/Badge:			Date:		
Data loaded into SED and accessible by others:					
Verified By/Badge:			Date:		

TABLE 5-4 (continued)
HPGe DATA VERFICATION CHECKLIST

GENERAL PACKAGE REVIEW

1. [YES] requires no action for the following checklist.
2. [NO] will require a response and [NA] may require a response. If NO, enter response in COMMENTS section at bottom of checklist.
3. Field logs should be checked for items that could affect data such as standing water in the field of view, topographic irregularities, surface vegetation, or visible soil heterogeneity.

	YES	NO	NA
1. Are the pre-op and post-op checks acceptable?	☐	☐	☐
2. Do the spectra appear normal and exhibit a lack of anomalies?	☐	☐	☐
3. Do micro-R readings indicate lack of radiological interference originating from outside the FOV?	☐	☐	☐
4. Do micro-R readings among measurements indicate homogeneous environment within the FOV?	☐	☐	☐
5. Is the error-weighted mean activity of the 63.2 and 92.6 keV lines $\geq$ 80% of the activity of the 1001.1 keV line for all spectra?	☐	☐	☐
6. Is the Th-232 error-weighted mean activity of the 338.4 and 583.1 keV lines $\geq$ 80% of the activity of the 911.1 keV line for all spectra?	☐	☐	☐
7. Is the Ra-226 error-weighted mean activity of the 351.9 and 609.3 keV lines $\geq$ 80% of the activity of the 1120.4 keV line for all spectra?	☐	☐	☐
8. Was the detector "dead time" $\leq$ 20% for all spectra?	☐	☐	☐
9. Was the K-40 peak resolution $\leq$ 3.0 keV for all spectra?	☐	☐	☐
10. Have the data been moisture corrected?	☐	☐	☐
11. Was the field soil moisture measurement $\leq$ 40% by weight for all spectra?	☐	☐	☐
12. Do the data seem reasonable, relative to other spectra and data within the data set?	☐	☐	☐
13. Were duplicate measurements taken?	☐	☐	☐
13a. For measured values $\geq$ MDC, were identified nuclides $\geq$ MDC in both spectra, thus allowing the precision of measurement to be assessed for all identified nuclides?	☐	☐	☐
13b. For all measured values $\geq$ MDC but < 5 x MDC, was the measurement difference $\leq$ MDC?	☐	☐	☐
13c. For all measured values $\geq$ 5 x MDC, was the RPD $\leq$ 20% for consecutive duplicate **OR** $\leq$ 35% for non-consecutive duplicate?	☐	☐	☐
14. Can the data be used without restriction or correction factors for intended purpose?	☐	☐	☐

COMMENTS:

TABLE 5-5
NaI DATA VERIFICATION CHECKLIST

☐ RSSI	☐ RSSII	☐ RSSIII	☐ RTRAK	☐ GATOR	☐ EMS
Project Name:				Project No.:	
Detector No:				Data Date:	
Completed By/Badge:				Date:	

LOCATION	File-Run No.	Qualifier	LOCATION	File-Run No.	Qualifier

Data copied to RTIMP/Labview folder:

Copied By/Badge: Date:

Data loaded in SED and accessible to others:

Verified By/Badge: Date:

GENERAL PACKAGE REVIEW

1. [YES] requires no action for the following checklist.
2. [NO] will require a response and [NA] may require a response. If NO, enter response in COMMENTS section of checklist.
3. Field logs should be checked for items that could affect data such as standing water in the field of view, topographic irregularities, surface vegetation, or visible soil heterogeneity.

	YES	NO	NA
1. Are the pre-op and post-op checks acceptable?	☐	☐	☐
2. Do the spectra appear normal and exhibit a lack of anomalies?	☐	☐	☐
3. Do micro-R readings indicate lack of radiological interference originating from outside the FOV?	☐	☐	☐
4. Do micro-R readings indicate a homogeneous environment within the FOV for all measurements?	☐	☐	☐
5. Was the GPS fix and differential correction satisfactory and the PDOP ≤6.0 for all measurements?	☐	☐	☐
6. Was the detector "dead time" less than 20% for all spectra?	☐	☐	☐
7. Were all spectra free of single and average energy calibration errors?	☐	☐	☐
8. Have the data been moisture corrected?	☐	☐	☐
9. Was the field soil moisture measurement ≤ 40 percent by weight for all spectra?	☐	☐	☐
10. Do the data seem reasonable, relative to other spectra and data within the data set?	☐	☐	☐
11. Can the data be used without restriction or correction factors for intended purpose?	☐	☐	☐

TABLE 5-5 (continued)
NaI DATA VERIFICATION CHECKLIST

COMMENTS (attach additional sheets if needed):

Total Spectra activity (cts/sec)	Max:_____	
Total Uranium (mg/kg)	Max:_____	Min:_____
Th-232 activity (pCi/g)	Max:_____	Min:_____
Ra-226 activity (pCi/g)	Max:_____	Min:_____

Total Spectra Obtained:_____ Rejected:_____ Remaining:_____

TABLE 5-6
INSTRUMENT SELECTION AND DETECTOR HEIGHT FOR EVALUATION OF FRL EXCAVATION BOUNDARIES AND CU DELINEATION IN HETEROGENEOUS AREAS

Scale of Heterogeneity (Radius in m)	Degree of Heterogeneity		
	Low Heterogeneity (<2x)	Medium Heterogeneity (2x-5x)	High Heterogeneity (>5x)
<0.5	Very small, low heterogeneous areas not of remediation concern for FRL boundary excavation or CU delineation	Very small, medium heterogeneous areas not of remediation concern for FRL boundary excavation or CU delineation.	Very small, high heterogeneous areas not of remediation concern for FRL boundary excavation or CU delineation
0.5-2.0	Small, low heterogeneous areas not of remediation concern for FRL boundary evaluation or CU delineation	Small, medium heterogeneous areas not of remediation concern for FRL boundary evaluation or CU delineation	Small, high heterogeneous areas not of remediation concern for FRL boundary evaluation or CU delineation
2.0-4.0	Small, low heterogeneous areas not of remediation concern for FRL boundary evaluation or CU delineation	Detectable by NaI and by HPGe at 31 cm detector height- May be of interest for CU delineation	Detectable by NaI and by HPGe at 1.0 m detector height. May be of interest for CU delineation
>4.0	Large, low heterogeneous areas detectable by NaI and HPGe at 1.0 meter detector height. Of interest for FRL boundary evaluation	Detectable by NaI and by HPGe at 1.0 m detector height. May be of interest for CU delineation	Detectable by NaI and by HPGe at 1.0 m detector height. May be of interest for CU delineation

TABLE 5-7
INSTRUMENT SELECTION AND DETECTOR HEIGHT FOR EVALUATION OF HOT SPOTS IN HETERGENEOUS AREAS

Scale of Heterogeneity (Radius in m)	Degree of Heterogeneity		
	Low Heterogeneity (<2x)	Medium Heterogeneity (2x-5x)	High Heterogeneity (>5x)
<0.5	Very small, low heterogeneous areas not of remediation concern; probably do not contain hot spots	Very small hot spots may be detectable by hand-held survey meters. Not of remediation concern	Very small hot spots detectable by hand-held survey meters and HPGe at 15 cm detector height
0.5-2.0	Small, low heterogeneous areas not of remediation concern; probably do not contain hot spots	Small hot spots detectable by HPGe at 15 cm detector height or possibly by NaI.	Small hot spots detectable by NaI and by HPGe at 31 cm detector height
2.0-4.0	Small, low heterogeneous areas not of remediation concern ; probably do not contain hot spots	Hot spots detectable by NaI and by HPGe at 31 cm detector height	Hot spots detectable by NaI and by HPGe at 1.0 m detector height
>4.0	Large, low heterogeneous areas detectable by NaI and HPGe at 1.0 meter detector height; but probably do not contain hot spots	Large hot spots detectable by NaI and by HPGe at 1.0 m detector height	Large hot spots detectable by NaI and by HPGe at 1.0 m detector height

TABLE 5-8
INSTRUMENT SELECTION AND DETECTOR HEIGHT FOR EVALUATION OF WAC EXCEEDANCES IN HETEROGENEOUS AREAS

Scale of Heterogeneity (Radius in m)	Degree of Heterogeneity		
	Low Heterogeneity (<2x)	Medium Heterogeneity (2x-5x)	High Heterogeneity (>5x)
<0.5	Very small, low heterogeneous areas not of remediation concern for WAC exceedances	Very small, medium heterogeneity areas not of remediation concern for WAC exceedances	WAC exceedances detectable by hand-held survey meters and HPGe at 15 cm detector height
0.5-2.0	Small, low heterogeneous areas not of remediation concern for WAC exceedances	Detectable by HPGe at 15 cm detector height, but not of remediation concern for WAC exceedances	WAC exceedances detectable by NaI and by HPGe at 31 cm detector height
2.0-4.0	Small, low heterogeneous areas not of remediation concern for WAC exceedances	Detectable by NaI and by HPGe at 31 cm detector height, but probably not of remediation concern for WAC exceedances	Detectable by NaI and by HPGe at 1.0 m detector height
>4.0	Large, low heterogeneous areas not of remediation concern for WAC exceedances	Large medium heterogeneity areas detectable by NaI and by HPGe at 1.0 m detector height and may contain WAC exceedances.	WAC exceedances detectable by NaI and by HPGe at 1.0m detector height

TABLE 5-9

MEASUREMENT UNCERTAINTIES IN DRY-WEIGHT RESULTS FOR THE NaI SYSTEMS (Relative Standard Deviations for Four-Second Measurements)

System	Relative Standard Deviation			
	U-238 (3×FRL)	U-238 (WAC)	Ra-226 (3×FRL)	Th-232 (3×FRL)
RTRAK	0.28	0.20	0.37	0.20
RSS1	0.27	0.20	0.36	0.20
RSS2	0.28	0.20	0.36	0.20
RSS3	0.28	0.20	0.36	0.20
EMS	0.27	0.20	0.36	0.20
Gator	0.28	0.20	0.37	0.20

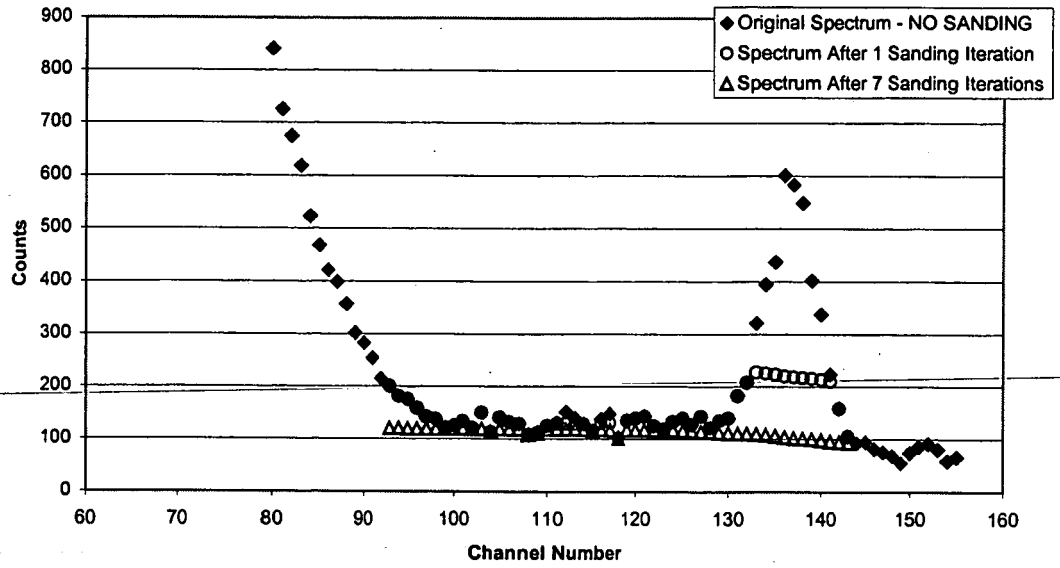


FIGURE 5-1. Illustration of the sanding process for a synthetic spectrum with one prominent peak. The figure shows the original spectrum and the sanded spectrum after 1 and 7 sanding iterations.

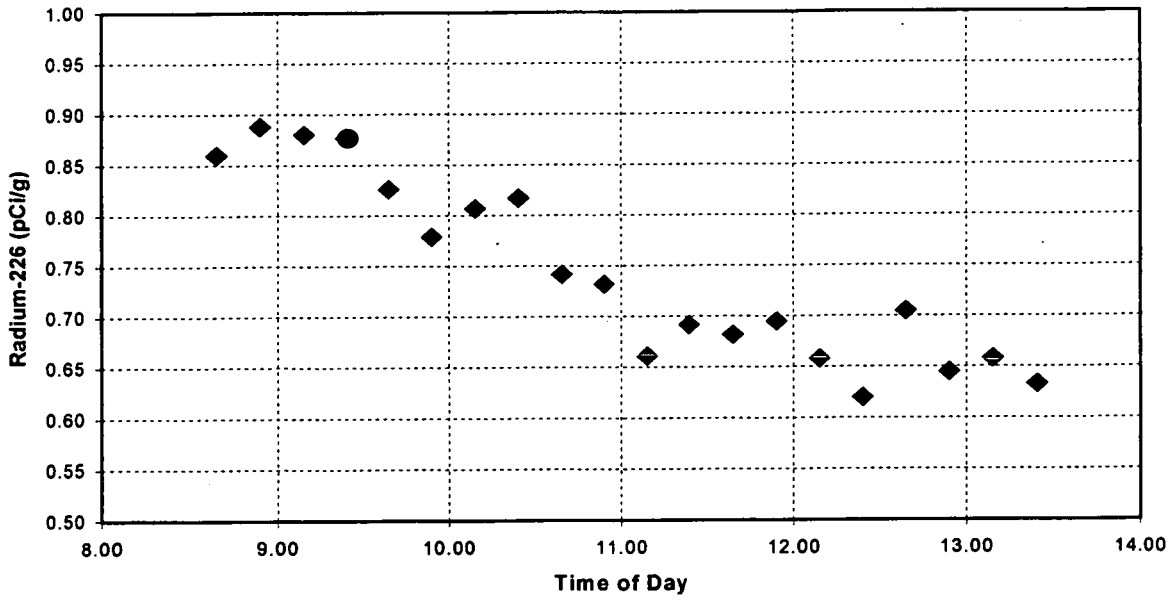


Figure 5-2. Radon Monitor Readings of Radium-226 (pCi/g) as a Function of Time

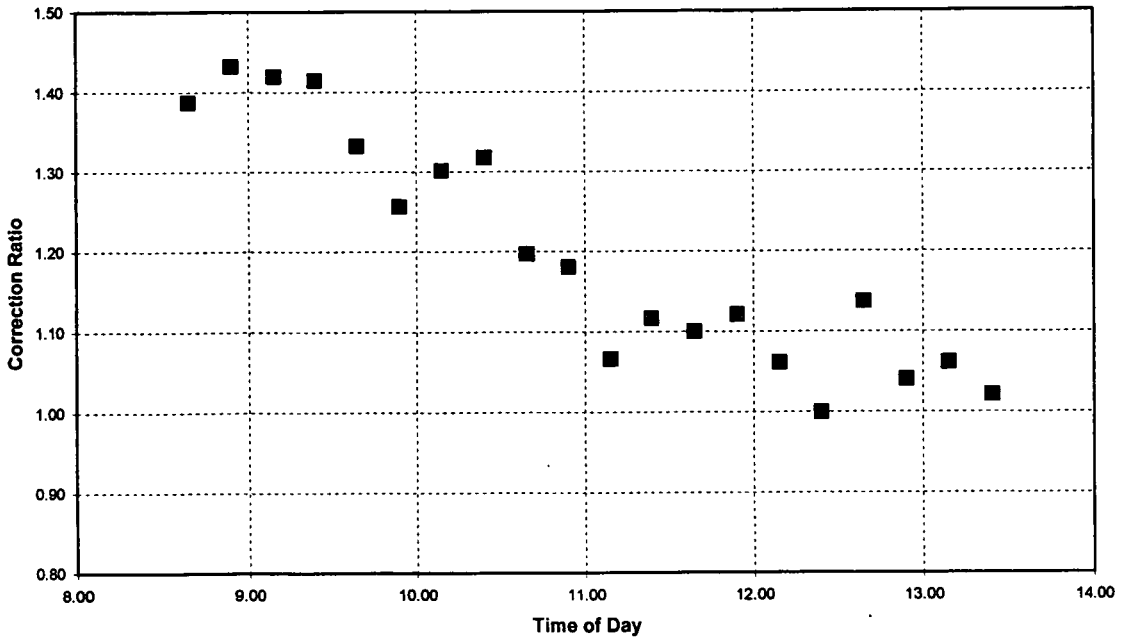


Figure 5-3. Diurnal Correction Ratio vs. Time

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GLOSSARY

The definitions given below refer to terms that might not be clear to readers of this manual. Below each definition, the reader is directed to the most important topic (or topics) in the main body of the document to which the defined term applies.

Aggregated Measurements – Combining two or more measurements, usually done to achieve a specified degree of precision or a specified minimum detectable concentration. For gamma spectrometry measurements, this is accomplished by adding the desired number of spectra together, channel by channel. The channel-by-channel addition of spectra yields a composite spectrum that is equivalent to the spectrum that would have been obtained from a single count of duration equal to the sum of the individual measurement times.

See: 4.8 Trigger Levels
4.15 Mapping Conventions

Comparability – Comparability refers to one of five criteria identified by the EPA to ensure data quality. It is a qualitative expression of the confidence with which one data set can be compared to another. Analytical data generated by the same analytical procedures are comparable provided that relevant, specified quality control elements, such as detection limits, initial and continuing calibration performance, accuracy, precision, and matrix interference acceptance criteria; are met or exceeded. Data for the same analytes generated by different analytical procedures are also comparable provided that relevant QC performance criteria similar to those above are met or exceeded.

See: 1.0 Introduction

Coverage (%) – Refers to the ratio of the cumulative area covered by a number of measurements (either NaI or HPGe) divided by the total surface area under investigation times 100.

See: 4.5 Detector Field of View and Area Coverage
4.6 HPGe Measurement Grid Configuration

Data Acquisition Time – Synonymous with "count time". The length of time a detector counts the number of gamma photons impinging upon it. HPGe data acquisition times are typically 5 minutes; NaI data acquisition times are typically 4 seconds.

See: 4.3 Time Required to Complete Scanning of a Remediation Area
2.0 *In situ* Gamma Systems Operated at the FCP
4.7 HPGe Data Acquisition Time

Data Quality Level – The combined type, number, and degree of rigorousness of specific quality assurance and quality control elements associated with analytical data.

See: 3.0 Use of *In Situ* Gamma Spectrometry Systems in the FCP Soil Remediation Program
4.1 Data Quality Levels

Data Quality Objective (DQO) – Qualitative and quantitative statements which specify study objectives, domains, limitations, the most appropriate type of data to collect, and the levels of decision error that will be acceptable for decision-making based upon the data.

See: 3.0 Use of *In Situ* Gamma Spectrometry Systems in the FCP Soil Remediation Program
4.1 Data Quality Levels

DQO Process – A quality management tool based on the scientific method and developed by the U.S. Environmental Protection Agency (EPA) to facilitate the planning of environmental data collection activities. The DQO Process enables planners to focus their planning efforts by specifying the use of the data (the decision), the decision criteria (action level), and the decision makers' acceptable error rates. The products of the DQO process are the DQOs.

See: 3.0 Use of *In Situ* Gamma Spectrometry Systems in the FCP Soil Remediation Program
4.1 Data Quality Levels

Detector Calibration – The process of calibration determines the relationship between counts per unit time registered by a detector and the concentration of various radionuclides in the soil in units of picoCuries per gram (pCi/g).

See: 5.2 Efficiency Calibrations for HPGe Systems
5.3 Efficiency Calibrations for NaI Systems

Detector Resolution – The ability in a detection device to distinguish between different measurement data. In a gamma spectrometer, detector energy resolution, or simply detector resolution, is expressed as the full peak width in energy units, keV, at half the maximum peak height (i.e., full width, half maximum; FWHM) of a spectal energy peak. On a comparison basis, sodium iodide detectors have a large FWHM (usually 50 to 60 keV) and thus poor resolution, while high purity germanium detectors have a small FWHM (usually 2 to 3 keV) and therefore good resolution. As a matter of convention at the FCP, the resolution of all HPGe gamma spectrometers is evaluated at the 1332.5 keV peak of cobalt-60 and NaI detectors at the 2614.6 keV peak of thallium-208.

See: 5.2 Efficiency Calibrations of HPGe Systems
5.3 Efficiency Calibrations of NaI Systems
4.2 Daily Energy Calibrations
5.9 Quality Control Considerations for Field Measurements

Field of View – The surface area that corresponds to the volume of earth from which 85 to 90 percent of the gamma photons that are detected by a stationary detector originate.

See: 4.5 Detector Field of View and Area Coverage
5.1.2 NaI Field of View

Fluence Rate – The number of gamma photons per unit area per unit time impinging upon a detector. This can be specified as a function of radial distance from the detector, depth in a soil column, or both. Typical units for this quantity are photons/cm^2 per second.

See: 4.5 Detector Field of View and Area Coverage
5.1.2 NaI Field of View
4.11 Surface Condition and Topographic Effects
4.13 Shine and Buried Sources

Gamma Rays, Gamma Photons – Electromagnetic radiation emitted primarily as a by-product of alpha or beta decay, whereby a nucleus loses surplus energy as it transitions from a higher excited state (higher energy level) to a lower excited state (lower energy level).

See: 4.5 Detector Field of View and Area Coverage

Heterogeneity – The degree of non-uniformity of radionuclide concentrations in soil. Heterogeneity must be specified in terms of the scale of the non-uniformity (i.e., non-uniform at the 1-inch scale, 1-foot scale, 1-meter scale, tens of meters scale etc.) with respect to the size of the field of view of gamma detectors.

See: 5.8 Contaminant Heterogeneity

High Purity Germanium Detector (HPGe) – The solid state hyperpure germanium crystal used for *in – situ* collection of gamma spectra. This crystal is mounted in a cryostat and connected to an electronics system for signal amplification and analysis.

See: 2.1 HPGe Systems and Measurements
See: 5.2 Efficiency Calibration for HPGe Systems

Minimum Detectable Concentration (MDC) – The MDC is the *a priori* concentration that a specific instrument and technique can be expected to detect 95 percent of the time. When stating the detection capability of an instrument, this value should be used. The MDC is the detection limit L_D multiplied by an appropriate conversion factor to give units of concentration, such as pCi/g (NRC 2000).

See: 5.4 Minimum Detectable Concentration

Pass – The movement of a NaI-detector platform (e.g., RTRAK, Gator, RSS) in a single, specified direction. Typical surveys move in alternate back and forth passes.

See: 4.5.2 NaI Detectors

Radiation Scanning System (RSS) – Name given to the NaI detector mounted on a 3-wheeled, manually pushed, cart.

See: 2.3 Radiation Scanning Systems and Measurements

Radiation Tracking (RTRAK) System – Name given to the NaI detector system mounted on a tractor that is used at the FCP.

See: 2.2 RTRAK System and Measurements

Remediation – For soils, remediation is the process whereby soil is progressively excavated until residual soil attains a regulatory limit in terms of the concentrations of the contaminants of concern. Thus, soil can be remediated with respect to WAC, with respect to hot spots, or with respect to FRLs.

See: 3.1 Predesign Investigations
3.2 Soil Excavation and Segregation
3.3 Precertifiation Investigations
3.4 Certification Investigations

Representativeness – Expresses the degree to which data accurately and precisely represent a characteristic of a population, a parameter variation at a sampling point, a process condition, or an environmental condition. Data representativeness is a function of sampling strategy; therefore, the sampling scheme should be designed to maximize representativeness.

See: 5.8 Contaminant Heterogeneity

Shine – Gamma rays detected by an NaI or HPGe detector that originate outside the normal field of view of that detector.

See: 4.13 Shine and Buried Sources

Sodium Iodide (NaI) Detector – A scintillation detector comprised of a NaI crystal, photomultiplier tube and associated electronics that is used for detection and measurement of gamma photons emitted by radioactive nuclei.

See: 2.2 RTRAK System and Measurements
2.3 RSS Systems and Measurements
2.4 Gator System and Measurements
2.5 EMS and Measurements

Total Activity – The summation of all detected decay events per unit time in a gamma spectrum. Total activity is typically expressed as counts per second and is obtained by dividing the total number of counts over a specific energy range, e.g., 50 to 3,000 keV, by the data acquisition time.

See: 4.14 Interpretation of NaI Total Activity Data

Trigger Level – A specified radionuclide concentration value that, if exceeded by an HPGe or NaI measurement, provides the basis for some subsequent action to be taken.

See: 4.8 Trigger Levels

WAC Exceedance – A contamination level that exceeds the On-Site Disposal Facility (OSDF) waste acceptance criteria (WAC). For uranium, the WAC is set at less than 1,030 mg/kg. Soil containing a concentration of uranium that equals or exceeds 1,030 mg/kg may not be placed in the OSDF. There are no WAC levels established for radium and thorium.

See: 4.9 Detection of Above-WAC Uranium Contamination
3.1.3 Above-WAC Detection, Confirmation and Delineation